1 MULTI-AGENT SYSTEM FOR SIMULATING LAND-USE/COVER CHANGE: A NEW MINDSET FOR AN OLD ISSUE

1.1 Background

1.1.1 The issue of land-use and land-cover change

Human alteration of the Earth is substantial and rapidly increasing. Change in land cover (i.e., biophysical attributes of the Earth's surface) caused by land use is the most substantial human-induced alteration of the Earth's system (Vitousek *et al.*, 1997). Because land ecosystems are important sources and sinks of most biogeochemical and energy fluxes on earth, land-use and land-cover change (LUCC), when aggregated globally, significantly affect key aspects of the Earth system's functioning (Lambin *et al.*, 2001). Between one-third and one-half of the land surface on earth has been transformed by human actions (Vitousek *et al.*, 1997). These massive global changes alter major biogeochemical cycles, thereby contributing substantially to local and global climate change (Chase *et al.*, 1999), including global warming (Houghton *et al.*, 1999). LUCC also causes irreversible losses of biodiversity worldwide (Sala *et al.*, 2000), and is a primary source of soil degradation (Tolba *et al.*, 1992 cf. Lambin *et al.*, 2001). Through modifying structures and functions of terrestrial ecosystems, LUCC significantly affects ecosystems' goods and services for human needs (Vitousek et al., 1997), subsequently influencing sustainable development.

Although not all of these impacts are negative, as some forms of LUCC in particularly developed regions are associated with continuing increases in food production or resource-use efficiency (Lambin *et al.*, 2003), the overall LUCC on earth has been a main source of global environmental degradation (Turner *et al.*, 1995; Lambin *et al.*, 1999; Lambin *et al.*, 2001). According to estimates, through the global expansion of croplands some 6 million km^2 of forests/woodlands and 4.7 million km^2 of savannas/grassland/steppes have been converted into agricutural land since 1850. Within these categories, respectively, 1.5 and 0.6 million km^2 of cropland have been abandoned (Ramankutty and Foley, 1999). According to the latest FAO assessment, from 1990-1995 there was a dramatic loss of 61.5 million hectares of tropical moist forests (i.e., the most diverse ecosystem in the world) in developing regions, while, at the same time, in developed countries the increase of forested areas was only 8.8 million hectares (Dolman and Verhagen, 2004). Modifications of land cover (i.e., changes in the structure over a short period), such as forest degradation caused by overexploitation, are also widespread (Archard *et al.*, 2002).

1.1.2 The need to model LUCC processes for supporting proactive land management

Relevant understanding of LUCC phenomena and underlying processes are crucial in identifying successful strategies for mitigating the adverse impacts of LUCC and adapting to the changing environment (Vlek *et al.*, 2003; Dolman and Verhagen, 2004). Rates and patterns of land-use change need to be understood to design appropriate biodiversity management. Areas of rapid LUCC need to be identified to focus land-use planning in the considered regions (Verburg *et al.*, 2003). However, although the understanding of the rates and patterns of LUCC, based on the measurements of past phenomena, is important for monitoring land cover and land use, it is still merely an *ex post* evaluation of the land-use management, reflecting a reactive attitude to environmental degradation.

Our view about environmental management has shifted fundamentally from a reactive to a more proactive management strategy. "*Life affects its environment*" and "*environment constrains life*", two statements of Gaia theory (Lovelock and Margulis, 1974 cf. Lenton and van Oijen, 2002: 265) mean that environmental change and feedback are inevitable (Lenton and van Oijen, 2002), and that environmental damage, once done, is very difficult to undo. This implies that maintaining ecosystems in the face of changes requires active management for a foreseeable future (Vitousek, 1997). Accordingly, the understanding of LUCC has shifted from a reactive and condemning view, which often criticizes human impacts on the environment, to a *proactive* view, which focuses on proactive management of land resources to avoid irreversible mistakes (Victor and Ausubel, 2000; Lambin *et al.*, 2003). Along with this viewpoint shift, the need for *ex ante* evaluation of policy options for proactive management of land resources becomes more urgent (Vlek *et al.*, 2003; Costanza and Gottlieb, 1998).

Ex ante evaluations of policy interventions in the uses and management of land resources require a more robust understanding of processes constituting LUCC, in order to anticipate the changes under different intervention scenarios (Vlek *et al.*, 2003).

Better data obtained from intensive monitoring alone are not enough for anticipation of future LUCC and its consequences unless causal mechanisms of the changes are better understood and modeled (Lambin *et al.*, 1999). Improved understanding of controlling factors and feedback mechanisms in land-use systems is important for more reliable projections and more realistic scenarios of future changes (Veldkamp and Lambin, 2001; Lambin *et al.*, 2003). These scenario studies provide a scientific knowledge that enables stakeholders, including policy makers, to proactively explore, discuss and examine potential outcomes (both benefits and costs) of different alternatives for intervention, thereby supporting policy-making processes for sustainable livelihoods and protecting the environment.

LUCC models are *reproducible* and *scientific reasoning tools* that can support the human's limited mental capacities in assessing land transformation and making more informed decisions about land resources management (Costanza and Ruth, 1998; Sterman, 2002). A model can be considered an abstraction of the real world, it should, however, be easy to understand and analytically manageable (Briassoulis, 2000). Because experimental manipulations or long-term studies for evaluating the performance of the complex human-environment systems are not possible or too costly, abstractive system models can help to fill the existing knowledge gaps (Costanza and Gottlieb, 1998; Sterman, 2002). LUCC models can offer a consistent and rigorous framework for identifying the scope of the problems, and highlight main causal loops within the system, thus enhancing our capacities in scientific reasoning about the likely outcomes in the future (Sterman, 2002). By clarifying and highlighting the main processes of land transformation, LUCC models can help to define environmental policy levers, i.e., points in the system where we should intervene to yield improved livelihoods and environmental qualities (Stave, 2002).

Most importantly, LUCC models can be used as *feedback tools* to facilitate learning and policy design. When rigorous LUCC simulation models are built and verified, they can serve as consistent tools to provide quick and relevant feedbacks in a form that allows stakeholders to revise and retest their ideas of interventions (Sterman, 1994). When stakeholders try the model and receive feedbacks about the likely effects of their tested interventions, their environmental learning (e.g., understanding and awareness of environmental consequences of actions) is also taking place. When the considered systems are complex, the discussions about how to solve a problem can bog down in disagreements about the likely effects of a given intervention. In this case, simulation models can act as a consistent feedback tool for scientific reasoning to enforce internal consensuses of actions (Forrester, 1987). In general, LUCC models can support policy decision-making processes by showing how our choices can affect the direction the future takes. Reflecting the overall importance of LUCC modeling in sustainable development studies, various LUCC models have been developed over the last few decades. Reviews of existing LUCC models are provided by Kaimowitz and Angelsen (1998), Briassoulis (2000), Veldkamp and Lambin (2001), and Agarwal *et al.* (2000).

Spatially explicit modeling is gaining awareness in LUCC studies. A model is called spatially explicit if a location is included in the representation of the system being modeled, and the model modifies the landscape on which it operates, i.e., spatial forms (e.g., maps) of a model's outputs are different to those of the model's inputs (Goodchild, 2001). Many reasons make spatially explicit modeling attractive in LUCC studies. A scientific reason is that many processes underlying land-use change are spatially dependent (Park *et al.*, 2003; Parker *et al.*, 2002). For example, land-use choices are constrained by biophysical factors that often vary across space. Furthermore, land-use capabilities often vary highly across space.

The most important reason for the increasing interest in spatially explicit LUCC modeling lies in the power of using spatial outputs for efficient communicating with stakeholders in land-use management and planning (Goodchild, 2001; Verburg *et al.*, 2003). This can help to improve participatory processes in research and development of land use and management. Spatially explicit representations of LUCC processes, e.g., the visual aids of Geographic Information System (GIS), are of very significant interest to the stakeholders, as most of them are not in a position to read technical papers/reports (Verburg *et al.*, 2003). At the community level, spatially explicit presentations of LUCC have also proven an appropriate means to support discussions with farmers about the distribution of resource bases, spatial interconnectivities between areas, and the consequences of local actions (Castella *et al.*, 2002a; Gonzalez, 2000; Rambaldi and Callosa 2000; Mather *et al.*, 1998; Smith *et al.*, 1999; Rambaldi *et al.*, 1998; Fox, 1995). At the policy decision-making level, spatially explicit presentations of LUCC modeling are suitable for communicating the results to policy makers (Verburg *et al*., 2003).

1.2 Problem analyses in LUCC modeling

As an old proverb states, “a problem stated is a problem half solved”. A rigorous analysis of the problems that earlier LUCC modeling has been confronted with is necessary before undertaking any modeling. Moreover, as many modeling methodologies and techniques exist, problem analyses will help us to select relevant modeling approaches, methodologies and techniques.

1.2.1 Complex nature of LUCC processes

The major challenge for achieving a better understanding of LUCC processes through modeling is the complex nature of the changes. Because land use is defined by the purposes for which humans exploit land cover, LUCC is obviously driven by complex interactions between biophysical and human factors over a range of scales in space and time (Parker *et al*., 2002; Verburg *et al*., 2003; Dolman and Verhagen, 2004). The *intrinsic complexity* of the coupled human-environment system underlying LUCC is characterized by the following aspects: (i) *nested hierarchies* of system components, (ii) *interdependencies* among system components, and (iii) *heterogeneities* of humans and their environment across time and space (Parker *et al*., 2002; Lenton and van Oijen, 2002; Eoyang and Berkas, 2002; Manson, 2001; Kohler, 2000). The following sections analyze these three aspects and subsequent problems in LUCC modeling.

Nested hierarchical structures and the problem of scale dependencies

The coupled human-environment system underlying LUCC is characterized by the *nested hierarchical structures* among the system components in space and time (Turner *et al*., 1995; Dumanski and Craswell, 1998; Verburg *et al*., 2003; Reynolds *et al*., 2003) (see Figure 1.1). A hierarchy is a partially ordered set of objects ranked according to asymmetric relations among these objects (Allen and Star, 1982; Shugart and Urban, 1988). The hierarchy theory suggests that a phenomenon at a certain level of scale (i.e., analyzed level) is explained by processes operating at the immediate lower level and constrained by processes operating at the immediate higher level, thus forming a "*constraint envelope*" in which the phenomenon or the analyzed process must remain (O'Neil *et al.*, 1989: 195; Gibson *et al.*, 2000: 225; Easterling and Kok, 2003: 269).

This means that a phenomenon such as LUCC is determined by factors at least at two different levels: above and below the level analyzed. The motions of driving factors in time and space are also different according to the differences of scale. The processes at the lower level are generally faster moving (shorter temporal extent) and lesser in spatial extent than the ones at the upper levels (Easterling and Kok, 2003). In other words, the behavior of any phenomenon, its causes and effects are scale dependent.

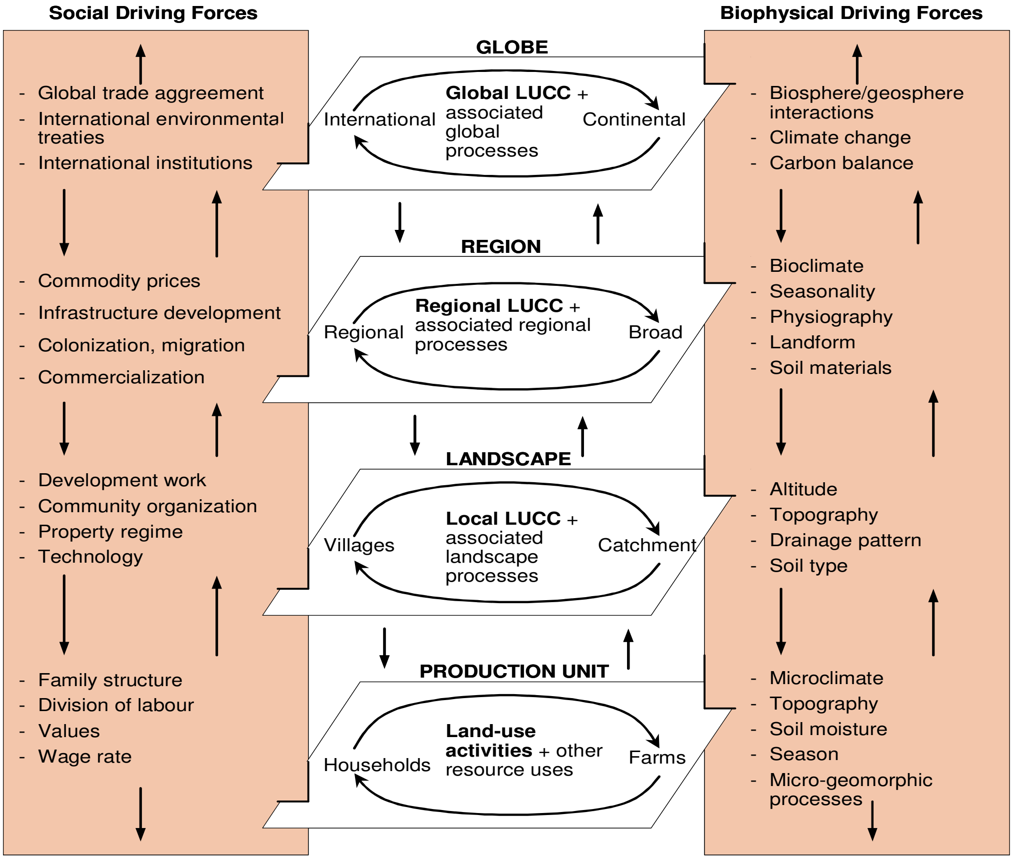

Figure 1.1 Land-use/cover change (LUCC) as the result of human-environment interactions over multiple scales in time and space. Sources: Adapted from Turner *et al.* (1995), Dumanski and Craswell (1998), and Verburg *et al.* (2003)

The reality of *scale dependencies* through the nested hierarchical structure of the human-environment system underlying LUCC suggests that straightforward aggregates of causes may not be sufficient to explain LUCC phenomena (Dumanski and Craswell, 1998; Lambin *et al.*, 2003; Verburg *et al.*, 2003). Unfortunately, many LUCC models are often operated at a single scale, which is usually selected arbitrarily or reasoned subjectively (Gibson *et al.*, 2000) without considering the intrinsic differences in scale of the causal factors (Verburg *et al.*, 2003). Some LUCC studies attempt to identify an optimal spatial scale or level of social organizations. However, because different processes underlying land-use change are important at different hierarchical levels, and the related criteria vary accordingly (Dumanski and Craswell, 1998). Land-use systems are likely never restricted to a single scale that can be regarded as optimal for measurements or predictions in the long term (Levin, 1992; Gardner, 1998; Geoghegan *et al.*, 1998; Turner, 1999; Gibson *et al.*, 2000; Verburg *et al.*, 2003).

Another approach may be the tracing through the hierarchies to specify every causal relationship of land-use change for every scale and organizational level, as well as rules for translating information across scales (Turner *et al.*, 1989). However, as the specification of causal relationships at each hierarchical level requires a specific dataset at such a scale (Dumanski and Craswell, 1998), it is very data demanding to formulate empirically all causal relationships of the complex nested hierarchical structure of the human-environment system. Furthermore, the mechanisms for transmitting cross-scale can be variable over time (Geoghegan *et al.*, 1998). Therefore, even if all causal relationships are empirically grounded at a particular point in time, there is still no guarantee that such a full set of causal relations will still be maintained in the next time frame.

Functional interdependencies and feedback loops in LUCC processes: the problem of non-linear and transformative dynamics

Interdependencies always exist between all the components of the coupled human-environment system underlying LUCC, both between components within the organizational level (horizontal interplay) and between components of different levels of organization (vertical interplay), across time and space (Young, 2002 cf. Lambin *et al.*, 2003). From the human side, land users may make their land-use decisions based on their land-use history and characteristics and surrounding biophysical environment. This leads to path dependencies and spatial interdependencies in land-use decision processes.

From the biophysical side, several spatially ecological interdependencies, such as slope processes, up- and down-stream effects, connectivity of natural habitats, ecological edge effects and forest gap dynamics, are crucial for the evolution of the coupled human-environment system, including LUCC (Parker *et al*., 2003).

The interdependencies among various causes of LUCC establish a causal web, i.e., one causal variable drives one or several others and vice versa (Turner, 1999; Lambin *et al*., 2003). Feedback loops carry materials, energy and information from one component to another (Bousquet and Le Page, 2004). These transforming feedback loops fuel the interdependence of the system by keeping the system components synchronized and interactive, serve to give both stability and changeability to the system, and support system evolution by providing impetus and resources for adaptation (Eoyang and Berkas, 1998; Manson, 2001).

Commonly, the landscape is taken to be in some kind of dynamic equilibrium: positive feedback loops exist and tend to amplify the land-use change (e.g., population growth often leads to rapid land-use/cover change), while some negative feedback loops co-exist and tend to counteract the change (e.g., institutional and improved land-use management may decrease the rate of adverse land-cover changes) (Lambin *et al*., 2003). Changes in driving forces can create disturbances in land ecosystems, but endogenous processes (e.g., vegetation growth/recovering) concurrently restore in part the system equilibrium (Geoghegan *et al*., 1998). The co-existence of buffering, amplification, and inversion of land transformation processes generate very non-linear dynamics in a land-use system, which have low predictability, high dimensionality, system openness, and dynamic (or far-from stable) equilibrium (Geoghegan *et al*., 1998; Eoyang and Berkas, 1998; Manson, 2001).

The reality of feedback loops among co-evolving components of the coupled human-environment system underlying LUCC challenges many assumptions of traditional LUCC models. Here, we point out the two main challenging points as follows:

First, there are *problems of multi-directional* and *endogenous causality* for statistical causal LUCC models, which follow the inductive approach. Many statistical LUCC models have the form: *LUCC = f(driving forces)*, where driving forces of LUCC (ranging from biophysical to socio-economic variables) are treated as exogenous causes of the change (see Lambin *et al.*, 2003). The affecting directions of causes are assumed to be consistent across time, space and human agents. However, with the existence of feedback loops, the causality of a phenomenon becomes inconsistent or multi-directional (Eoyang and Berkas, 1998), i.e., a variable can be either exogenous (cause of the change) or endogenous (response to the change) to the land-use change (Lambin *et al.*, 2003). For example, expansion of road networks can be a cause of rapid deforestation, but sometimes agricultural potential or development requirements of already deforested lands may lead to policy decisions to expand the road networks in these areas (see Lambin *et al.*, 2003).

In a broader view, LUCC is a function of not only socio-economic and biophysical variables, but also of itself (Geoghehan *et al.*, 1998). This actually means that, as the time scale of analysis expands, all causes of land-use change become endogenous to the human-environment system and are affected in some degree by previous land-use change (Lambin *et al.*, 2003). The pathway of this effect is that temporally accumulative LUCC leads to significant impacts on the land ecosystem goods and services, consequently affecting human livelihoods and other socio-economic conditions, and thus creating new opportunities and constraints for future land use (Lambin *et al.*, 2003).

Second, when interdependencies combine with the complicated nested hierarchical structure of the coupled human-environment system, feedback loops become enormous, creating the *problem of tractability* for any purely analytical LUCC model. A purely analytical/mathematical LUCC model, e.g., system dynamics models, describes the system using a causal loops diagram, which maps explicitly all possible interdependencies among possible causes and is represented by a complete set of differential equations (Forrester, 1980; Gilbert and Troitzsch, 1999). For instance, full representation of a system of 2 objects requires 4 equations: 2 to describe how each object behaves by itself ("*isolated*" behavior equation), 1 to describe the interaction between the two objects ("*interaction*" equation), and 1 to describe how the system behaves without the objects ("*field*" equation). In general, the number of required equations is defined by the "power law of computation": 2^n, where n is the number of objects in the system (Easterling and Kok, 2003: 275). If a system has 10 objects, the number of differential equations needed is $2^{10} = 1024$. The complex land-use system