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Feedbacks in socio-environmental land systems

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Abstract: The dynamics of socio-environmental systems are driven by exogenous forces and by the interaction of endogenous system components, both within the social and environmental realms, as well as between them. In recent years, the number of models and modelling frameworks explicitly representing feedbacks has increased, especially for models of land use systems. Land use changes are on the one hand caused by a complex interaction of human and/or institutional land use demands and the environment, which supports or limits human use in several aspects. On the other hand, land use changes and their effects at least partly influence the respective driving forces and future land-use decisions, e.g. by affecting the productivity of agricultural land, in- or decreasing the quality of life in (residential) urban areas, increasing accessibility and thereby facilitating the economic development of areas and so forth. In this paper we address the complexity of socio-environmental systems via analysing and reviewing the feedbacks implemented in current simulation models, with a focus on feedback loops between the social and the environmental component. We developed an analysis framework distinguishing several categories of information exchange between model components. Results indicate that feedbacks from 'population' simulated e.g. as households or average land managers were well represented, whereas institutions or technical changes were rarely addressed. From the environment component mostly the performance of crops or density of population were reported, whereas other environmental changes e.g. concerning soil, weather or water dynamics or structural changes in cities were addressed less frequently or not at all. We conclude that the land-use modelling community started to address system complexity via implementing feedback loops, leaving much room for increasing the realism of information exchange between representations of the social and the environment components.

Keywords: feedback mechanisms; land use modelling; review; urban and rural land systems.

1. INTRODUCTION

Land is a limited resource, especially if we consider land, which is suitable for specific land-use purposes such as agriculture, forestry, livestock-production, housing, recreation or cultural activities. The dynamics of such systems are determined by (1) the initial state of the land system, (2) external (or exogenous) driving forces and (3) internal feedback loops, which may be positive or negative. In system dynamics, the term feedback is used to characterize a bidirectional relation between two or more system components (Morrison 1991), which is exactly the way we use the term in this paper. We clearly distinguish feedbacks from unidirectional relations, which are called drivers, or driving forces (Geist and Lambin 2002), or impacts from the perspective of the affected component. In the land-use literature, instead of the term 'feedback' other terms are frequently used, such as link, (complex) interaction, coupled system, connection. For these terms, the authors often not clearly define whether just one component is influencing another one, or whether both influence each other, i.e. whether the relations they address are uni- or bidirectional (e.g. Liu et al. 2007;Parker et al 2008; Rindfuss et al. 2008; Schaldach and Priess 2008; Verburg 2006; Walsh et al. 2008, Young et al. 2006).

Humans interact with the environment in various ways. Historically, research on these interactions has been split into research on the effects of human actions on the environment and on the effects of environmental changes on human well-being. Coupled socio-environmental systems have been addressed by natural / ecological and social sciences, and the attention for the topic has considerably increased over the last two decades (Science Direct: from 2,800 papers in 1990 to 21,000 papers in 2009)[1]. While both scientific realms agree on the importance of understanding the dynamics of socio-environmental systems, they disagree on explanatory approaches (Turner and Robbins 2008), which is also reflected in the range of methodologies of the studies reviewed in this paper. While the complexity of human-environment interactions (here: socio-environmental feedbacks) has been noted early (Marsh et al. 1864), approaches that tackle complexity via addressing the feedbacks between both subsystems have kicked in manly during the last decade (see Table 1). This can be attributed to the separation of ecological and social sciences (Rosa & Dietz 1998; Liu et al. 2007). The evolving Land-Use Science (also called land change science, e.g. Turner & Robbins 2008) is trying to embrace approaches from either side, contributing to generate new insights into the multiple dimensions of social and environmental subsystems involved in land-use dynamics (GLP 2005). While drivers of land-use dynamics have been analysed in detail (Angelsen and Kaimowitz 1999; Geist and Lambin 2002), to date no systematic approach is available for classifying feedback mechanisms and analysing how they contribute to explain land-use dynamics, although the scientific community seems to agree about the importance to study and simulate the complexity e.g. feedback mechanisms in land systems (GLP 2005[2]; Liu et al. 2007, Parker et al. 2008, Young et al. 2006).

Recent reviews of land use models tackled feedbacks in several ways. Alberti (2008) analysed feedback loops between environmental and human system and distinguished various spatio-temporal scales. In their review of urban models, Haase and Schwarz (2009) differentiated feedbacks (1) of land use and human sphere, (2) of environment and human sphere, and (3) between local and regional scale. Schaldach & Priess (2008) identified socio-environmental feedbacks in land-use models for regional to global scale. Finally, Verburg (2006) distinguished three types of feedbacks (1) between driving factors and the effects of land use change, (2) between local and regional processes, and (3) between agents of land use change and the spatial units of the environment.

This paper seeks to contribute to the maturation of land use science (Rindfuss et al 2008) by analysing important feedbacks in socio-environmental land systems and how they are implemented in the models generated and used by the scientific community. The aims of this paper are thus twofold: first, to provide a framework for analysing feedbacks in socio-environmental land use systems, and second to review existing simulation models of land use systems regarding the feedbacks included. In the review part of the paper, we address the following research questions:

- Which feedbacks are tackled / neglected?
- Which elements of the social and environment components are addressed?
- On which (temporal and spatial) scales do simulated feedbacks occur?

2. METHODS AND DATA

2.1 Analysis Framework

At the global scale, we argue that the only external drivers are the solar activity and the parameters of the orbit, while all other dynamics are endogenous to the system. This per-

[1] The search term (link* OR interaction* OR feedback* OR couple*) AND (land*use OR land*cover or agric* OR urban) AND model AND (human OR social OR societ* OR agent* OR actor*) for the period 1990-2009 (2010/03/15), resulted in 986 (1.029) hits in WEB of KNOWLEDGE, 158,000 (166,800) hits of journal & book articles in SCIENCE DIRECT; and 17,400 (17,600) hits including citations in GOOGLE SCHOLAR.

[2] With this paper we explicitly contribute to themes 1.2 (How Do Changes in Land Management Decisions (…) Affect Biogeochemistry (…) of Terrestrial and Freshwater Ecosystems?) and 2.3 (How are Ecosystem Services Linked to Human Well-being?) of the GLP Science Plan (GLP 2005).

spective has been addressed and simulated by Meadows et al. (1972), or with considerably more detail in the GUMBO model (Boumans et al. 2002). At regional or local scales, we expect quite different sets of external drivers (Geist and Lambin 2002) and endogenous feedbacks, which are responsible for the dynamics of land systems, partly originating from human decisions and activities, and partly related to environmental processes and functions and the services they provide for society (e.g. MEA 2005; Rudel et al. 2005; Lambin and Meyfroidt 2010). The differentiation between external drivers and endogenous feedbacks is then a matter of system boundaries. The socio-environmental systems we are addressing in this paper are conceptually divided into two major components: (1) The social component, comprising elements such as persons or households (population), organisations, but also economic sectors or technology, and (2) the environment (be it natural or manmade such as urban or agricultural), including all biophysical properties and processes (see GLP 2005; Schaldach and Priess 2008). At least two types of feedbacks (Figure 1) can be distinguished in these systems, which we here define as:

TYPE 1: feedback between major components
TYPE 2: feedback within major components

TYPE 1 feedbacks between major components of socio-environmental land systems comprise a wide variety of human activities such as where and when to use land for a certain purpose and how to use it (plant potatoes or wheat; build a hut or a castle; irrigate or not; expand land use or abandon a piece of land; protect land for nature conservation or carbon accumulation). The second half of the loop includes all types of environmental changes in functions and services, which are influencing human (land use related) activities and decision making. In either of the social and the environment component cascades of internal (TYPE 2) feedbacks may occur, depending on the social, spatial and temporal scales and resolutions at which the authors study and analyse land systems. It is noteworthy that simple representations of socio-environmental land systems can lack TYPE 1 feedbacks, for example if soils and weather or other environmental conditions are represented as static rather than dynamic elements, resulting e.g. in stable crop yields. Depending on the richness of details included in the models, TYPE 2 feedbacks might be covered implicitly or explicitly. Note that TYPE 1 feedbacks might also pass through TYPE 2 feedbacks before the loop is closed.

Both types of feedbacks as defined above are essential for either stabilising land-use (e.g. a farmer keeps growing potatoes as long as crop yields and prices are within the range of expectations), or triggering land-use transitions, for example if functions or services pass threshold values (Lambin and Meyfroidt 2010).

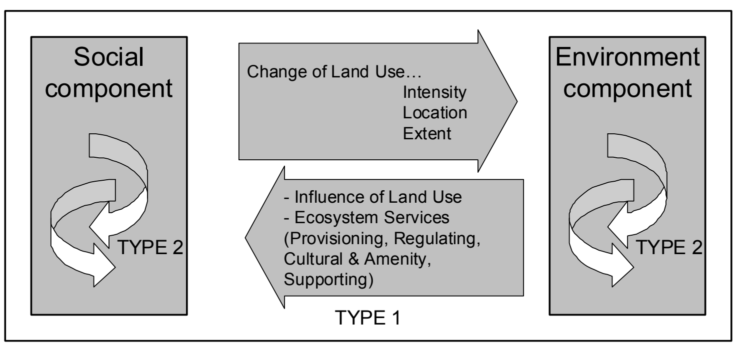

Figure 1. Feedbacks in socio-environmental systems. Since feedbacks are defined as bidirectional, TYPE 1 feedbacks cover the complete loop between the social and the environment component.

To add more detail to the analysis of feedbacks, the social and the environment component were divided into sub-systems[3]. The social component encompasses *Population, Economy, Politics/Planning, Culture*, and *Technology*. The category *Population* covers the dynamics

[3] In the remainder of section 2, all categories used in this study are printed in italics.

of population including migrating households as well as quality of life and human health. The category *Economy* relates to economic activities including farming practises, while *Politics / Planning* refer to decisions made by policy makers like changes in subsidies, property rights, or protection status of land. The environment component consists of the sub-systems *Built environment, Biodiversity, Vegetation/Crops, Soil/Biochemistry, Hydrology and Atmosphere*. As far as possible, the feedback analysis is addressing the sub-systems involved. Note that only in cases where the social component was represented without identifiable sub-systems, we used the classification '*Whole human system*'.

Table 1. Case studies for which feedbacks have been analysed.

Source	**Continent**	**Simulation method**[4]	**Thematic focus (one or more)**					
			urban	rural	hydrology / water use	agriculture	natural vegetation	migration
Berger (2001)	S/C-America	ABM		X	X	X		
Claessens et al. (2009)	Europe	Regression		X		X		
Costanza et al. (2002)	N-America	ODE	X	X	X	X	X	
Engelen et al. (2007)	Europe	CA	X					
Eppink et al. (2004)	not specified	ODE	X				X	
Evans and Kelley (2004)	N-America	ABM		X		X	X	X
Hellden (2008)	Africa	ODE		X		X		
Holzkaemper and Seppelt (2007)	Europe	GA		X		X		
Landis and Zang (1998)	N-America	Regression	X					
Le et al. (2008)	Asia	ABM		X		X		
Lee et al. (2008)	Asia	Regression	X	X		X		
Liu et al. (2008)	N-America	Various		X	X	X		
Manson (2005) / Parker et al. (2008)	S/C-America	ABM		X	X	X	X	X
Matthews and Pilbeam (2005)	Asia	ABM/ODE		X		X		
Oel et al. (2010)	S/C-America	ABM		X	X			
An (2005) / Parker et al. (2008)	Asia	ABM		X			X	
Deadman (2005) / Parker et al. (2008)	S/C-America	ABM		X		X	X	X
Parker et al. (2008)	not specified	ABM		X	X	X	X	X
Priess et al. (2007a,b)	Asia	CA/ODE		X		X	X	X
Priess et al. (2010)	Asia	CA/ODE		X	X	X		
Salvini and Miller (2005)	N-America	ABM	X					
Seppelt and Voinov (2003)	N-America	GA		X	X	X		
Stephenne and Lambin (2001)	Africa	ODE		X		X		
van Delden (2007)	Europe	CA		X		X		
Verburg and Overmars (2007)	not specified	Regression	X	X		X		
Waddell (2002)	N-America	ABM	X					
Walsh et al. (2006)	Asia	CA		X		X	X	
Walsh et al. (2008)	S/C-America	CA		X		X	X	

From the social to the environment component, the following aspects of changing land use are distinguished: *Intensity, Location*, and *Extent*. *Intensity* refers to aspects like density, amount of fertiliser used, or irrigation and the like. *Location* encompasses (re-) location of certain land uses in a spatially explicit way, such as building new houses or allocating crops. Finally, *Extent* covers changes in the area covered by a land use type.

[4] ABM – Agent Based Model; CA – Cellular Automata; GA – Genetic Algorithm; ODE – Ordinary Differential Equations.

From the environment to the social component, the direct influence of land use is addressed, because the presence or absence of a land use in an area might influence social processes like location choices of households depending on existing built-up areas or other factors. Additionally, influences of environmental sub-systems are captured using the ecosystem services (ESSs) concept. The Millenium Ecosystem Assessment (2005) grouped ESSs into the categories: *Provisioning, Regulating, Cultural* and *Supporting*. For each of the models under review, we analysed, which of these feedback categories are incorporated.

2.2 Selection Process and Case Study Characteristics

For the review presented in this paper, the following criteria were used to select studies on models simulating socio-environmental systems:

- published in peer-reviewed literature.
- focusing on land issues (urban, rural and natural areas; including studies on land - freshwater & land - coastal waters).
- preferably process- or rule-based, to be able to link processes and feedbacks.
- preferably applied at the regional to local scale because studies tend to be less aggregated and to have a more explicit and detailed representation of socio-economic and biophysical processes and feedback loops.

Based on the criteria above, 28 modelling studies have been reviewed (see table 1). They cover a wide variety of topics, including urban simulation (7), agriculture (21), water management (8), natural vegetation (10) and migration (5). The following modelling techniques are used, with some modelling studies combining two or more methods: cellular automata (6), agent-based models (9), system dynamics models (4), regression models (4) and optimisation methods (2). Geographically, the case studies cover all major regions except Australia and Antarctica: 7 are located in Asia and in North-America, 4 in Europe, 5 in South and Central America, 2 in Africa and 3 model applications could not be related to a specific region.

3. RESULTS

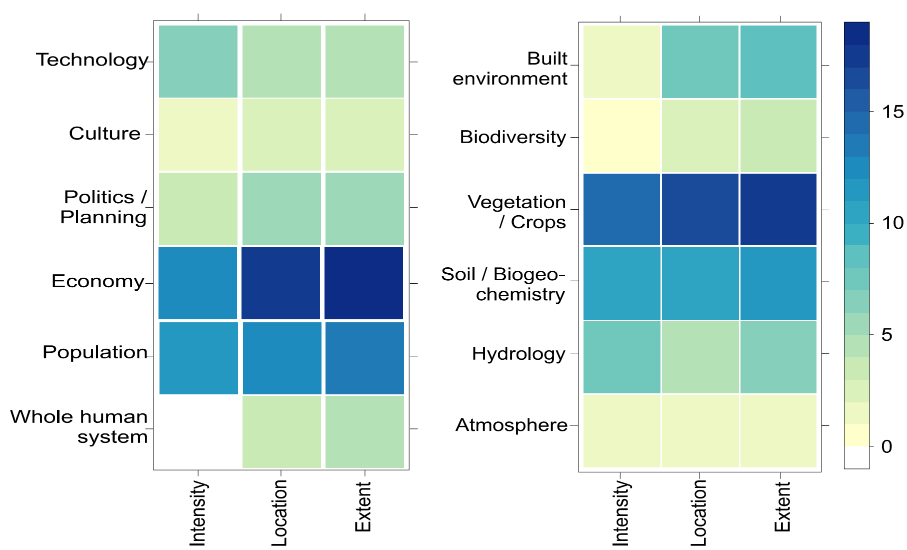

Figure 2. Feedbacks from the social component via land use (2a, left) to the environment component (2b, right). The colours code the number of times a feedback has been observed in the reviewed case studies (white: no feedback; dark: highest number of feedbacks). The x-axis represents 3 different aspects of land use

We started tackling the feedbacks of the social and environmental components of the modelling studies by analysing the types of land use changes that are related to various social sub-systems (Figure 2a). The majority of feedbacks originates from the Economy or the Population sub-systems. In the models analysed, the sub-systems of Technology, Planning / Politics, and Culture are much less represented in land use change decisions and information flowing to the environment components. Related to the latter, we noted that changing land use intensity is less often modelled than extent or location of certain land use types. The second step was to analyse the influence of these types of land use changes onto the environmental sub-systems (Figure 2b). Vegetation/Crops and Soil/Biochemistry are the two environmental sub-systems that are influenced the most, hinting at the larger number of agricultural modelling studies in the review. Hydrology and the Built Environment are also directly addressed, whereas issues relating to Biodiversity and the Atmosphere are rarely tackled. However, they might be influenced by TYPE 2 feedbacks occurring within the environmental component. Land use intensity, location, and extent are all relevant for influencing the various environmental sub-systems.

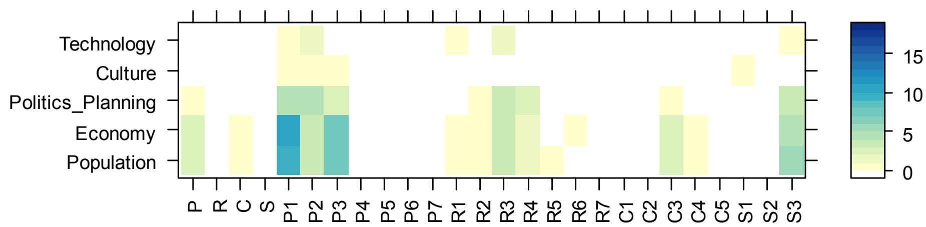

Figure 3. Feedbacks from the environment component via ecosystem services to the social component. The y-axis represents ESSs[5], which trigger the effects in the models. P- provisioning, R – regulating, C – cultural, S – supporting. The colours code the number of times a feedback has been observed in the reviewed case studies (white: no feedback; dark: highest number of feedbacks).

ESSs are an important pathway linking the environment to the social component of land systems (Figure 3). Whenever possible we identified single ESS, of which the most frequently used are food provisioning (P1), water provisioning (P2) wood & fibre provisioning (P3), recreation and tourism (C3) and nutrient cycling (S3). Regulating services are mostly water related (amount & quality), but also including air, climate and soils. Figure 3 also highlights that many potentially important feedbacks via ESSs were not addressed at all, including all major categories – provisioning (anorganic, biochemical) – regulating (pest control, natural hazards) – cultural (heritage, spiritual) – supporting (biodiversity, soil formation). The social sub-systems addressed in the studies mainly refer to population and economy, as these two sub-systems are the most likely to be modelled explicitly, whereas Politics / Planning and Culture are often only implicitly included in scenario configurations.

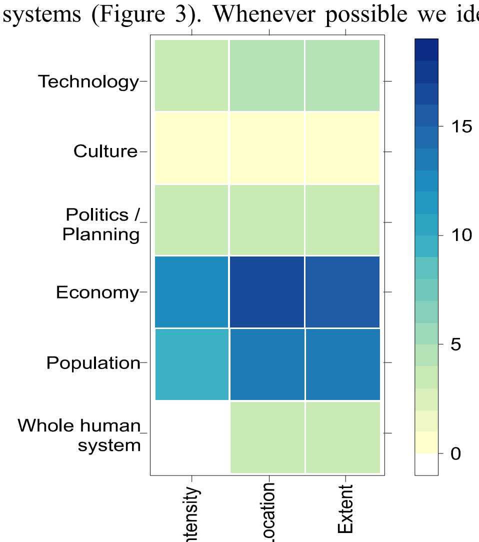

Figure 4. Feedbacks from the environment component via land use to the social component. The colours code the number of times a feedback has been observed in the reviewed case studies (white: no feedback; dark: highest number of feedbacks).

[5] P1 - food; P2 - freshwater storage and retention; P3 – wood, fiber & fuel; P4 - Inorganic resources; P5 - biochemical & medicinal resources; P6 - genetic materials; P7 - ornamental species; R1 - air quality regulation; R2 - climate regulation; R3 - water quantity; R4 - water quality; R5 - Soil retention & erosion protection; R6 - natural hazard mitigation; R7 - biological regulation & pest control; C1 - cultural heritage; C2 - spiritual & artistic inspiration; C3 - tourism and recreation; C4 – aesthetic; C5 - science & education; S1 - biodiversity & nursery; S2 - soil formation; S3 - Nutrient Cycling

Technologies are mainly present in the form of agricultural practises such as fertiliser use and irrigation, either simulated in process models or via regression coefficients, in either case influenced by crop yields, soil fertility or both. In turn, technologies influence the yield expectations, revenues and land-use decisions of agents or other units of decision-making. Note that the categories e.g. Politics / Planning or Economy do represent a wide variety of different pathways, scales and economic sectors, depending on the major purpose, location and spatio-temporal scale of the study.

Finally, land use can directly link the environment and the social components. The majority of the modelling studies represent those feedbacks by addressing Economy or Population (Figure 4). This is again due to the fact that Economy and Population are the social sub-systems that are most likely to be included dynamically rather than as scenario constraints. Thus, only a few studies consider effects on Policy / Planning, technological or cultural effects. The most important changes in land use considered are the changes of location and of the extent of land use. Land use intensity as well is included in a large fraction of the studies.

4. DISCUSSION AND CONCLUSIONS

Our analysis shows that the land use community started to represent a range of categories of feedback loops in their models. Various representations of social sub-systems such as households, economic sectors (or the economic reasoning of simulated decision-making) are exchanging information with sub-systems of the environment such as crops/vegetation, hydrology or soils. The term feedback (loop) is not at all limited to 1:1 relationships regarding the flow of information between the two conceptual main components, but is also comprising 1:n and m:1 relationships. For example, detailed agent-based models sending various classes of information to their biophysical environment (expansion of farm, plant crop *x* in location *y*, irrigation with technology *u*; settle in zone *w*), “expect” and receive only crop yield levels and distances from the environment component, estimated without any changing weather or soil conditions. The reverse has also been found, i.e. reporting detailed environmental dynamics to “average” decision-makers.

While the majority of studies focus on rural areas and agricultural production, environmental feedbacks from weather, hydrologic and soil conditions are rarely included. As a consequence, decisions simulated for land use transitions like deforestation, which are involving rapid changes in carbon, water and nutrient status of soils, might on the one hand be biased or even spurious. A similar conclusion holds for urban models, in which residents decide upon their location choice with only limited feedbacks of the environment regarding changing living conditions due to human-made restructuring the city. On the other hand, many cellular automata, system dynamics and regression models still provide only “average” land use and management decisions as input for their environment components. Thus, the internal representation of complexity, processes and TYPE 2 feedbacks built into social and environment components is also influencing the amount and categories of TYPE 1 feedbacks between the components (see examples in the previous paragraph). Although many socio-environmental models seem to be developed by multi-disciplinary teams, the old divide between social science and economy vs. natural science and geography and the approaches they preferably use, is also at least partly reflected in the categories of implemented feedbacks. Another example for deficits is including different levels of decision-making in agent-based models or cellular automata. Among others, this encompasses aspects like spatial planning or real-estate developers for urban regions or regional authorities controlling agricultural practices. On one hand it is expected that additional components and feedback loops better explain the complexity of land systems and add more realism to simulations, but on the other hand more feedbacks also require additional data or assumptions and introduce more degrees of freedom and new uncertainties.

Although not always explicitly reported, annual decision-making seems to be a common scheme in most of the 28 studies, triggering cascades and feedbacks both within the components (TYPE 2) and information exchange with the environment components (TYPE 1).

Time lags, occurring for example if intra-annual decisions are required, are treated in different ways. Firstly, predefined land-management strategies are executed between feedback events, even if (process) models of high temporal resolution (monthly, daily) are used to represent environmental components (e.g. the DAYCENT model employed by Priess et al. 2007, 2010). Second, Berger (2001) seems to use a higher frequency of feedbacks between decision-making and the availability of irrigation water (monthly). A third option to bridge temporal gaps makes use of capabilities of environmental models like DAYCENT (Parton et al. 1998; also employed in Priess et al. 2007, 2010) or SWAT (Arnold and Fohrer, 2005) to simulate certain intra-annual land-management decisions like irrigation or fertilisation, triggered by environmental feedbacks, such as soil water status. In the latter case, decision-making and the corresponding feedback loop is partly shifted from the social to the environment component (e.g. in Priess et al. 2010). Water availability and water management/use can also be used to analyse how feedbacks are working across spatial scales. For example Liu et al. (2008) employ a whole suite of models in the SAHRA framework to bridge spatial scales, addressing three levels to transport water management information from the regional scale to the pixel. Others like e.g. Berger (2001), Costanza et al. (2002) or Priess et al. (2010) aggregate water availability from the pixel to the (sub-) catchment scale, at which the information is passed to the simulated water managers/users. Water users decide to irrigate their farm-pixels either based on water rights and crop type (combined agent-based model/cellular automata of Berger 2001), or agricultural pixels based on a multi-criteria suitability assessment and crop type (in the PLM model of Costanza et al. 2002 or in the SITE model of Priess et al. 2010).

To date, only a limited degree of real-world complexity is captured by including feedback loops in current models of land systems. While the model developers' selection of TYPE 1 (and TYPE 2) feedbacks to capture the complexity and characterise the dynamics of land systems is mostly motivated by the objectives of the study (e.g. research questions directed towards prediction or process understanding; decision support with or without stakeholder involvement), it is less clear why specific feedbacks are neglected. Important feedbacks we expected to be addressed (based on the focus of the study) were not implemented, e.g. agricultural land use has been studied without (direct or indirect) feedback from soils or weather (dry or wet conditions) or urban development has been analysed without considering effects of spatial planning. Furthermore, in some studies it was difficult to identify feedbacks between the different components, because the verbal description of the processes involved left (too) much room for interpretation. The deficits identified may be related either to limited know-ledge or process understanding, or data constraints, or to the scientific concepts / perspectives of the model developers differing from our expectations, or to limitations of the state of the art, or simply to the limited amount of time and resources available for model development. However, ex-post analyses like this review always bare the risk of partly misinterpreting the objectives of modelling studies or model structures, thus over- or underestimating scientific progress or limitations.

As previous work on land use drivers has shown (Angelsen and Kaimowitz 1999; Geist and Lambin 2002), the systematic analysis and classification of elements of land systems has contributed considerably to the progress of the evolving land-use science, and particularly the development of (predictive) models as argued by Loveland et al. (2003). In a similar manner, we expect that the systematic analysis of feedback mechanisms in existing models contributes to identify recent advances and limitations in land-use modelling and ultimately our insights into the dynamics of real-world socio-environmental systems. We consider this review as a first step, as we could only briefly address feedbacks across spatial and temporal scales, while the techniques how different feedbacks have been implemented could not be tackled at all. Additionally, more models need to be analysed to identify successful simulation strategies (Parker et al., 2008). Other types of feedbacks e.g. between different land systems need to be analysed as argued by Liu et al. (2007), contributing to advance the representation and understanding of complex systems.

REFERENCES

Alberti, M., Modeling the Urban Ecosystem: A Conceptual Framework, in: Marzluff, J.M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley, G., Ryan, C., Simon, U., ZumBrunnen, C., (eds.), *Urban Ecology. An International Perspective on the Interaction Between Humans and Nature*, Springer 2008.

Angelsen, A., and Kaimowitz, D., Rethinking the Causes of Deforestation: Lessons from Economic Models, *The World Bank Research Observer*, 14 (1), 73–98, 1999.

Arnold, J.G., and Fohrer, N., SWAT2000: current capabilities and research opportunities in in applied watershed modelling, *Hydrological Processes* 19, 563-572, 2005.

Berger, T., Agent-Based Spatial Models Applied to Agriculture: a Simulation Tool for Technology Diffusion, Resource Use Changes, and Policy Analysis, *Agric. Econ.* 25, 245-260, 2001.

Bouwmans, R., Costanza, R., Farley, J., Wilson, M.A., Portel, R., Rotmans, J., Villa, F., Grasso, M., Modeling the dynamics of the integrated earth system and the value of global ecosystem services using the GUMBO model, *Ecol. Econ.,* 41, 529–560, 2002.

Claessens, L., J.M., Schoorl, P.H., Verburg, L., Geraedts, A., Veldkamp, Modelling interactions and feedback mechanisms between land use change and landscape processes, *Agriculture, Ecosystems and Environment* 129, 157–170, 2009.

Costanza, R., Voinov, A.A., Boumans, R., Maxwell, T., Villa, F., Wainger, L., Voinov, H., Integrated ecological economic modelling of the Patuxent River watershed, Maryland, *Ecological Monographs*, 72 (2): 203–231 2002.

Deadman, P., Household Decision Making and Patterns of Land Use Change in LUCITA: An Agent Based Simulation of the Altamira Region, Brazil, MODSIM 2005, Melburne, Australia, 2005.

Engelen, G., Lavalle, C., Barredo, J., van der Meulen, M., White, R., The Moland Modelling Framework for Urban and Regional Land-use Dynamics, in: Koomen, E., J., Stillwell, A., Bakema, H.J., Scholten (eds.), Modelling Land-Use Change, Progress and Applications, *Springer*, Dordrecht, pp 297-319, 2007.

Eppink, F., van den Bergh, J., Rietveld, P., Modelling biodiversity and land use: urban growth, agriculture and nature in a wetland area" *Ecol. Econ.,* 51 (3-4), 201-216, 2004.

Evans, T.P., and Kelley, H., Multi-Scale Analysis of a Household Level Agent-Based Model of Land-cover Change, *Journal of Environmental Management*, 72, 57-72, 2004.

Geist, H.J., Lambin, E.F., Proximate causes and underlying driving forces of tropical deforestation", *BioScience*, 52 (2), 143–150, 2002.

GLP, Global Land Project Science Plan, IGBP report 53. pp 74, 2005.

Haase, D., and Schwarz, N., Simulation Models on Human-Nature Interactions in Urban Landscapes: a Review Including Spatial Economics, System Dynamics, Cellular Automata and Agent-based Approaches, *Living Reviews in Landscape Res.*, 3, 2009.

Hellden, U., A coupled human-environment model for desertification simulation and impact studies, *Global and Planetary Change*, 64, 158-168, 2008.

Holzkämper, A., R. Seppelt, LUPOlib – A generic library for optimising land-use patterns and landscape structures, *Environmental Modelling & Software*, 22, 1801-1804, 2007.

Landis, J., Zhang, M., The second generation of the California urban futures model. Part I: Model logic and theory, *Environment and Planning B*, 25 (5), 657-666, 1998.

Lambin, E.F. and Meyfroidt P., Land use transitions: Socio-ecological feedback versus socio-economic change. *Land Use Policy* 27, 108–118, 2010.

Le, Q.B., Park, S.J., Vlek, P.L.G., Cremers, A.B., Land-Use Dynamic Simulator (LUDAS): A multi-agent system model for simulating spatio-temporal dynamics of coupled human–landscape system. I. Structure and theoretical specification, *Ecological Informatics*, 3, 135-153, 2008.

Lee, C.L., Huang, S.L., Chan, S.L., Biophysical and system approaches for simulating land-use change, *Landscape and Urban Planning,* 86, 187–203, 2008.

Liu J.G., Dietz T., Carpenter S.R., Alberti M., Folke C., Moran E., Pell A.N., Deadman P., Kratz T., Lubchenco J., Ostrom E., Ouyang Z., Provencher W., Redman C.L., Schneider S.H. & Taylor W.W., Complexity of coupled human and natural systems. Science, 317, 1513-1516, 2007.

Liu, Y., Gupta, H., Springer, E., Wagener, T., Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management, *Environmental Modelling & Software*, 23, 846-858, 2008.

Loveland, T.R., Gutman, G., Buford, M., Chatterjee, K., Justice, C.J., Rogers, C., Stokes, B., Thomas, J., Land use/land cover change. in: Strategic plan for the climate change science program. US Climate Change Science Program, Washington, 118–134, 2003.

Manson, S.M., Agent-modeling and genetic programming for modeling land change in the Southern Yucatan Peninsular region of Mexico, *Agriculture, Ecosystems & Environment*, 111, 47-62, 2005.

Marsh, G.P., Man and Nature. *Harvard University Press*, Cambridge, MA., 1864.

Matthews, R.B. and C., Pilbeam, Modelling the long-term productivity and soil fertility of maize/millet cropping systems in the mid-hills of Nepal, *Agriculture, Ecosystems & Environment*, 111 (1-4), 119-139, 2005.

MEA, Millennium Ecosystem Assessment, Ecosystems and Human Well-being: Synthesis, Island Press, Washington, DC, 2005.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W., III, The limits to growth, New York, *Potomac Associates*, 1972

Morrison F. (1991). The Art of Modeling Dynamic Systems. Wiley, New York, pp 387.

Parker, D.C., Entwisle; B., Rindfuss; R.R., Vanwey, L.K., Manson; S.F., Moran; E., An; L. Deadman; P., Evans; T.P., Linderman; M., Mussavi Rizi, M., Malanson, G., Case studies, cross-site comparisons, and the challenge of generalization: comparing agent-based models of land-use change in frontier regions, *Journal of Land Use Science*, 3(1), 41 – 72,. 2008

Parton, W.J., Harmann, M., Ojima, D.S., Schimel, D., DAYCENT and its land surface submodel: description and testing, *Global and Planetary Change*, 19, 35–48, 1998.

Priess, J.A., M., Mimler, A.M., Klein, S., Schwarze, T., Tscharntke, I., Steffan-Dewenter, Linking deforestation scenarios to pollination services and economic returns in coffee agroforestry systems, *Ecological Applications,* 17 (2), 407-417, 2007.

Priess, J. A.; Mimler, M., Weber, R., Faust, H., Socio-environmental impacts of land use and land cover change at a tropical forest frontier, in Oxley, L., and Kulasiri, D. (eds), MODSIM 2007, International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2007, 349-357, 2007.

Priess, J.A., C., Schweitzer, F., Wimmer, O., Batkhishig, M., Mimler, The consequences of land-use change and water demands in Central Mongolia – an assessment based on regional land-use policies, *Journal of Land Use Policy*, in print, 2010.

Rindfuss; R.R., Entwisle; B., Walsh; S., An; L., Badenoch; N., Brown; D.G., Deadman; P., Evans; T.P. Fox; J., Geoghegan; J., Gutmann; M., Kelly; M., Linderman; M., Liu; J., Malanson; G.P. Mena; C.F., Messina; J.P., Moran; E.F., Parker; D.C., Parton; W., Prasartkul; P., Robinson; D.T. Sawangdee; Y., Vanwey; L.K., Verburg, P.H., Land use change: complexity and comparisons, *Journal of Land Use Science*, 3 (1), 1 – 10, 2008.

Rosa E.A. & Dietz T. (1998). Climate change and society - Speculation, construction and scientific investigation. Int. Sociol., 13, 421-455.

Rudel, T.K., Coomes, O.T., Moran, E., Achard, F., Angelsen, A., Xu, J., Lambin, E.F., Forest transitions: towards a global understanding of land use change, *Global Environmental Change Part A*, 15 (1), 23–31, 2005.

Salvini, P., Miller, E., ILUTE: An Operational Prototype of a Comprehensive Microsimulation Model of Urban Systems, *Net. & Spat. Econ.,* 5 (2), 217-234, 2005.

Schaldach, R., Priess, J A, Integrated Models of the Land System: A Review of Modelling Approaches on the Regional to Global Scale, *Liv. Rev. in Lands. Res.*, 2 (1), 1-34, 2008

Seppelt, R., and A., Voinov, Optimization Methodology for Landuse Patterns: Evaluation based on Multiscale Habitat Pattern Comparison, *Ecol. Model.,* 168 (3), 217-231, 2003

Stephenne N. & Lambin E.F. (2001). A dynamic simulation model of land-use changes in Sudano-sahelian countries of Africa (SALU). Agric. Ecosys. Environ. 85, 145-161.

Turner B.L. & Robbins P. (2008). Land-Change Science and Political Ecology: Similarities, Differences, and Implications for Sustainability Science. Ann. Rev. Environ. Res., 33, 295-316.

van Delden, H., Luja, P., Engelen, G., Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management, *Environmental Modelling & Software*, 22, 223–238, 2007.

van Oel, P.R., Krol, M.S., Hoekstra, A.Y., Taddei, R.R., Feedback mechanisms between water availability and water use in a semi-arid river basin: A spatially explicit multi-agent simulation approach, Environmental Modelling & Software, 25, 433-443, 2010.

Verburg P.H. (2006). Simulating feedbacks in land use and land cover change model. *Landscape Ecology*, 21, 1171-1183.

Verburg P, Overmars K, 2007, Dynamic Simulation of Land-use change Trajectories with the CLUE-s Model", in Modelling Land-Use Change, Progress and Applications Eds E Koomen, J Stillwell, A Bakema, HJ Scholten (Springer, Dordrecht) pp 321-335

Waddell, P., Modeling Urban Development for Land Use, Transportation, and Environmental Planning, *Journal of the American Planning Association*, 68 (3), 297-314, 2002.

Walsh, S.J., Entwistle, B., Rindfuss, R.R., Page, P., Spatial simulation modelling of land use/land cover change scenarios in northeastern Thailand: a cellular automata approach, *Journal of Land Use Science*, 1 (1), 5–28 2006.