International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Representation of environmental dynamics in models of socio-environmental systems

Joerg A. Priess [a] **and Christian Schweitzer** [a]
[a] *Helmholtz Centre for Environmental Research (UFZ),*
Department Computational Landscape Ecology (CLE),
Permoserstr. 15, D-04318 Leipzig, Germany

Abstract: Environmental changes can be related to naturally occurring phenomena or human activities such as land use. Considering that more than three quarters of the global land surface have been and are currently altered by humans, societies and their biophysical environments as coupled socio-environmental systems (SES) are more prominent than natural ecosystems. In many instances, people are directly or indirectly affected by environmental changes, and changes in environmental properties and dynamics (soil quality, water levels, forest growth, rainfall …) vice versa often change human decisions and behaviour. Due to these bidirectional influences, we emphasise the need for (more) accurate representations of environmental changes and dynamics in SES-studies, to avoid spurious or biased estimates of the production of food, feed or other goods and services. In this paper we present examples of environmental changes and how they may trigger reactions in the social system, with a special focus on demonstrating how the feedbacks from environmental dynamics are or could be represented in SES-models.

Keywords*: Biophysical environment; cellular automata model; decision-making; multi-agent system;* socio-environmental system - SES

1 INTRODUCTION

Environmental changes can be related to land-use activities, naturally occurring phenomena or global change processes. Land-use changes are most obvious if caused by single events or if land-cover changes or conversions are involved, such as turning natural vegetation into agricultural land or grasslands or converting fertile land to urban use. Less obvious, but just as important are environmental changes caused by continuous use or environmentally unsustainable agricultural practises involving processes like erosion, nutrient mining, or the accumulation of nitrogen, agrochemicals or salts . Naturally occurring environmental changes may either be triggered by single often catastrophic events such as landslides or floods, or longer lasting phenomena such as droughts or weathering and soil formation or climate change.

There is little doubt that even at global scale environmental conditions have strongly been altered by human activities forming anthropogenic biomes like dense settlements, villages, crop- and rangelands, in total affecting more than 75% of the terrestrial surface [Ellis and Ramankutty 2008]. Similarly, hydrological cycles and water tables have changed considerably for example due to irrigated agriculture [India: Rodell et al. 2009]. Other examples are observed and simulated losses of carbon stocks, based on deforestation and land-use change [Amazonia: Malhi et al. 2008; Soares-Filho et al. 2006]], or nutrient dynamics of agricultural systems [Africa: Haileselassie et al. 2007].

The examples given above are based on a broad range of different direct and indirect methods to measure (or estimate) environmental dynamics and changes. An important common aspect of all of these reported environmental changes is that they all sooner or later become relevant for decisions related to the use of the corresponding resources. Consequently, land-management decisions or expected productivities of natural resources will result in spurious estimates if based on outdated or insufficiently specified environmental status or environmental dynamics. Thus the lack of biophysical information may negatively affect short-term individual goals such as production or profits, but also long-term societal goals such as the sustainable use of resources Given that knowledge about environmental dynamics and their impacts relevant for decision making, it is obvious that a time lag occurs between the generation of new knowledge and its implementation in simulation models.

Considering societies and their biophysical environments as coupled socio-environmental systems – SES [Redman et al. 2004], changes in environmental properties frequently affect biodiversity, the productivity of natural and anthropogenic ecosystems and in turn often influencing or changing human decisions and behaviour. Due to the close feedbacks between environmental dynamics, decision making and wellbeing of human societies, we emphasise the need for a more accurate representations of environmental change processes in studies of socio-environmental systems. We do not aim at other levels of detail in SES-studies and -models, but emphasize the need for an improved representation of environmental change and/or dynamics to avoid spurious results assuming static or stable biophysical conditions, or erroneous assumptions about the dynamics of the biophysical environment.

The main objective of this paper is to analyse how environmental dynamics could be represented in models of socio-environmental systems to improve the representation of decision-making. We present examples of environmental changes and how they may influence or trigger reactions in the social system,.

2 REPRESENTATION OF ENVIRONMENTAL DYNAMICS IN SES

From the fact that more than three quarters of the ice-free terrestrial surface are or have been transformed by humans [Ellis and Ramankutty 2008], it follows that the vast majority of terrestrial systems have to be considered as SES in which human societies interact with their biophysical environment (Figure 1). In these biophysical environments, societies have adapted to changing conditions for millennia, but also caused (accidental) environmental changes or damages from a human perspective. Often rationales are, among other factors, related to a misinterpretation of environmental indicators [Gunderson and Holling 2001].

As depicted in Figure 1, information about environmental status and dynamics is required at different levels of decision-making, although environmental processes might sometimes lack corresponding units in the social system to manage them [Pelosi et al. 2010]. In the following sections we will explain how a representation of dynamically changing biophysical environments can be implemented in two different widely applied modelling approaches i.e. (i) “Multi-Agent-Systems” (MAS) and (ii) models based on “Cellular-Automata” (CA).

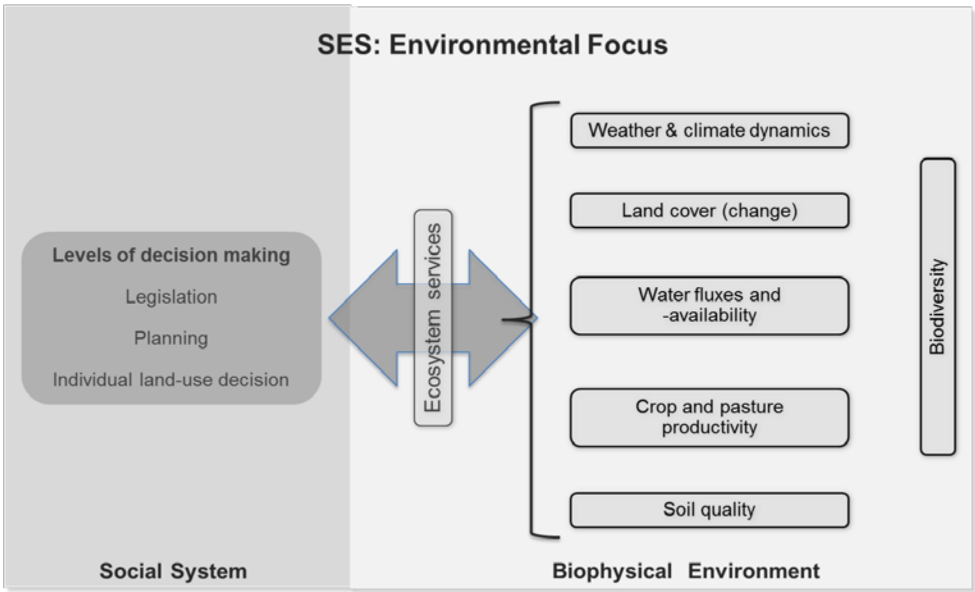

Figure 1. Representation of environmental status and -dynamics in SES. Links between the components of the biophysical environment and the social system are not shown. (adapted from GLP [2005] and Schaldach and Priess [2008])

2.1 Real-world examples

Higher (hierarchical) levels of decision-making in administration and planning not necessarily require more aggregated environmental information than the individual level. Flood prevention in river basin management, the quality of drinking water or compliance with regulations to receive environmental payments are examples for precise (and partly also timely) information needed at various administrative levels, whereas for the assessment of land cover, crop yields or similar variables aggregated or mean values may be sufficient. Often threshold levels are defined, such as a certain water level, or water quality indicators, beyond which environmental changes trigger decisions in the social system. At the level of individual or household decisions, environmental information may not only be relevant as absolute values, but can also trigger adaptation for example crop or management choices as relative values in a regional context, or changes over time. Reactions/adaptations to environmental changes may vary widely depending on individual objectives or on information communicated via the media or extension services.
Additionally, environmental thresholds such as low water levels may generate hierarchical responses in the social system such as a prohibition to irrigate crops. These real-world examples demonstrate that different strategies are needed in SES-models to transmit information of environmental status and/or changes to the algorithms simulating decision-making.

2.2 Examples for representing environmental dynamics in SES-models

The concepts presented in this section have been motivated by various simulation studies using either MAS or CA models [Berger et al. 2007; Hurkens et al. 2008; Le et al. 2010; Manson 2005; Parker et al. 2003; Priess et al. 2011; Walsh et al. 2008]. Model-components simulating decision-making based on MAS or CA, are both capable to “perceive” environmental changes, however using quite distinct

concepts. In MAS (Figure 2 left) it is possible to define different types of agents and their interactions, for example to simulate households (or people) acting in diverse ways to biophysical information, or representing different institutions or levels of decision-making. The geographical context and other biophysical information may be represented by other types of agents or by grid-cells (=pixels). CA-based models (Figure 2 right) usually use a “pixel for people” approach, which means a pixel or a group of pixels represent a location in a study region and simultaneously mimic decisions for example at the household or individual (farmer) level. Different levels of decision-making can be based on different sets of cell-groups, for example “responsive” to water levels or water availability to simulate river basin management.
In MAS and CA models different strategies can be applied to represent or simulate environmental dynamics or changes. In case no feedbacks between the social system and the biophysical environment are relevant (or of interest), changing conditions such as weather or climate can simply be read from a database. In this example one or more levels of the social systems react or adapt to environmental changes, but the biophysical environment cannot not be influenced by activities of the social system. However, as argued above, human activities gave rise to and are still causing environmental changes, calling for more elaborate strategies in which social and environmental dynamics and changes are at least partly simulated endogenously causing mutual effects. In a very simple representation, the social system would perceive one environmental indicator for example water availability or a crop yield level, take a decision, act and subsequently change the environment by acting in a certain fashion. More complex approaches are receptive to more environmental signals, being communicated between, or being specific for different agents (MAS) or levels of decision-making (MAS & CA). In both modelling approaches it is possible to simulate adaptations to environmental changes, e.g. by “remembering and comparing” past and recent information, or by relating the “own” environmental situation – be it as agent or as pixel - to the status of other agents or cells following both cases, a certain strategy can be based on the own relative or fixed, but also to adapted threshold values.

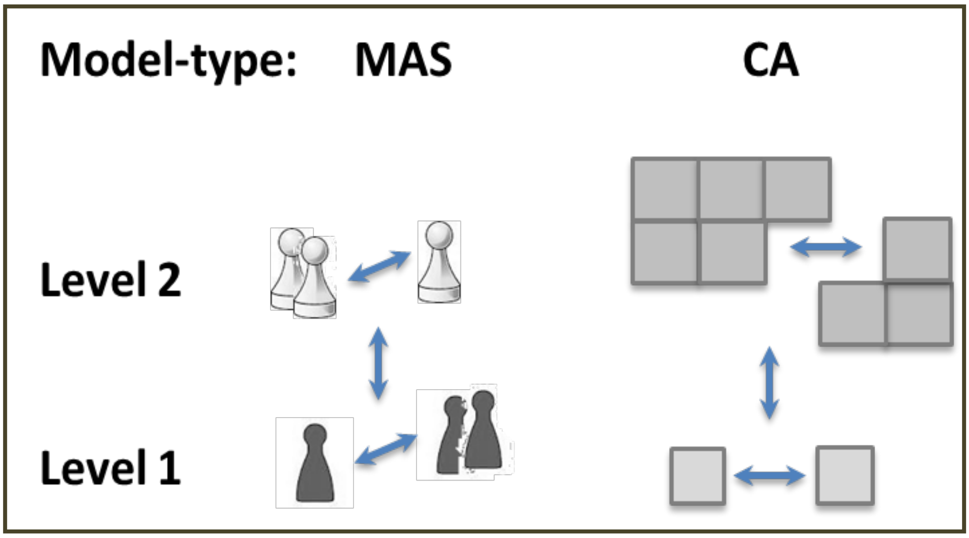

Figure 2. Units perceiving environmental information in MAS and CA models. MAS (left): different communicating agents at two levels of decision-making CA (right): single communicating pixels or clusters of pixels exchanging information simulating units of decision-making at different levels.

3 DISCUSSION

The urgent need for an improved monitoring of environmental conditions, especially in regions of intensive land-use activities, has been clearly addressed (e.g. GLP [2005]), aiming at expanding our knowledge of coupled SES [Liu et al. 2007; Redman et al. 2004], and to improve their representation in SES models. An excellent example for environmental monitoring is the publicly available satellite-based monitoring system of deforestation of the Amazon - the PRODES Programme, which is perhaps the most advanced deforestation surveillance scheme in the world (www.obt.inpe.br/prodes/index.html).

In this paper we presented some of the links between environmental changes and decision-making, mainly based on land-use examples. By using two frequently applied simulation approaches, we have shown how environmental dynamics can be linked with decision-making in SES-models. We argue that even with simple representations of environmental dynamics/changes, for example with reduced or no interaction between agents or “decision-making” pixels, errors in terms of land demands, crop yields, management strategies or economic returns can be considerably reduced [Berger et al. 2007; Das et al. 2011; Le et al. 2010; Priess et al. 2011]. Addressing changing biophysical environments is especially important, when longer time periods are considered e.g. to explain historical land-use dynamics or scenarios of potential future changes (e.g. climate change, intensification of land use, etc.). The key to improve calculations/estimates is to make the information of changes in biophysical conditions available for the different levels of simulated decision making, which may involve the communication or processing of environmental information in the social sub-system. In modelling studies the latter would apply to any type of decision algorithm, irrespective of the methodology or mathematical approach used to represent the perception of and the reaction/adaptation to environmental changes. The above applies to (slowly) accumulating effects such as soil depletion, potentially not causing any reaction for several years, but also to conditions triggering an immediate response, if for example water availability falls below a threshold needed to provide irrigation water or cooling water for industrial or energy production.

It has also been argued [Feld et al. 2009; Seppelt et al. 2011] that information about environmental conditions and dynamics is essential for the assessment of biodiversity, the provision of ecosystem goods and services and the benefits derived for human wellbeing [Potschin and Haynes 2011; Harrison et al. 2010]. Current simulation models of socio-environmental systems seem to focus on the representation of a relatively small number of environmental variables and ecosystem services, which can be derived [Priess et al. 2010], confirming the demand for a stronger emphasis on environmental data and models as tools to analyse them [GLP 2005], also as a prerequisite for more reliably deriving ecosystem services [Seppelt et al. 2011].

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