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A framework for modeling payments for ecosystem services with agent-based models, Bayesian belief networks and opinion dynamics models☆

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ABSTRACT

We present an integrated modeling framework for simulating land-use decision making under the influence of payments for ecosystem services. The model combines agent-based modeling (ABM) with Bayesian belief networks (BBNs) and opinion dynamics models (ODM). The model endows agents with the ability to make land-use decisions at the household and plot levels. The decision-making process is captured with the BBNs that were constructed and calibrated with both qualitative and quantitative information, i.e., knowledge gained from group discussions with stakeholders and empirical survey data. To represent interpersonal interactions within social networks, the decision process is further modulated by the opinion dynamics model. The goals of the model are to improve the ability of ABM to emulate land-use decision making and thus provide a better understanding of the potential impacts of payments for ecosystem services on land use and household livelihoods. Our approach provides three important innovations. First, decision making is represented in a causal directed graph. Second, the model provides a natural framework for combining knowledge from experts and stakeholders with quantitative data. Third, the modular architecture and the software implementation can be customized with modest efforts. The model is therefore a flexible, general platform that can be tailored to other studies by mounting the appropriate case-specific "brain" into the agents. The model was calibrated for the Sloping Land Conversion Program (SLCP) in Yunnan, China using data from participatory mapping, focus group interviews, and a survey of 509 farm households in 17 villages.

1. Introduction

Land-use changes affect the long-term functioning of natural ecosystems that are crucial for human well-being (Foley et al., 2005; MA, 2005). A thorough understanding of spatial and temporal changes in the land system is therefore of paramount importance when designing management and policy strategies that promote sustainable land use and preserve the benefits humanity derives from ecosystems. Recently, market-oriented instruments, such as programs of payments for ecosystem services (PES), have been gaining importance as a policy tool for directing land use to sustainable pathways. Many PES schemes provide monetary incentives to motivate land users to alter their decision making to be in line with a desired conservation outcome (Ferraro and Kiss, 2002).

However, an effective evaluation of PES programs that target sustainable land-use change is challenging because of the fundamental integration of social and ecological processes, the dynamic nature of the cause and effect chains, and the necessary consideration of feedback effects and nonlinearities. Conventional tools, such as statistical analysis, yield only part of the picture because they often fail to include longer-term perspectives and emerging system properties. Moreover, the consideration of temporal and spatial outcomes is crucial for several reasons, including the nonlinear responses of farm households to changes in external framework conditions or the evolution of new habitat structures in response to land-use incentives.

To address the complexities of such coupled systems, we propose a hybrid agent-based modeling approach to comprehensively simulate the effects of payment schemes on changes in land use and livelihoods. We include an empirical application for the Sloping Land Conversion Program (SLCP) in China, one of the world's largest PES programs, which compensates farmers for converting cropland to forest and grassland. Agent-based models (ABMs) are bottom-up approaches that provide a natural way of both conceptualizing and implementing complex, dynamic, and disaggregated models of human decision-making (Le et al., 2010; Valbuena et al., 2010). ABM are increasingly popular and can be

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effective in modeling coupled socioecological systems such as land-use change, which is a cumulative result of individual land users' decisions (Bonabeau, 2002; Parker et al., 2003; Valbuena et al., 2008). ABMs have also been applied to examine the impact of PES on land-use decisions (see, e.g., Chen et al., 2012; Deffuant et al., 2002b; Sengupta et al., 2005).

One of the major advantages of ABMs is their ability to model decision-making entities (Rindfuss et al., 2004; Turner II et al., 2007). Hence, the validity of ABMs depends on their ability to model individual behavior, which is a major challenge due to the complexity of human actions (Grimm et al., 2005; Parker et al., 2003; Smajgl et al., 2011). Many ABMs rely on heuristic rules or single-objective optimization models to describe the decision making of agents. Consequently, agents are often assumed to act in an economically rational way (Balmann, 1997; Filatova et al., 2009; Parker et al., 2008; Schreinemachers and Berger, 2011). Such models have substantial explanatory power, for instance, in describing the evolution of farms or entrepreneurs in competitive market settings (Happe et al., 2006). However, human behavior is often irrational and subjective due to limited knowledge and information or because of personal preferences and beliefs. Thus, humans employ a variety of strategies in land-use decisions that go beyond the maximization of profits or minimization of risk (Bonabeau, 2002; Parker et al., 2008). The optimization approaches based on microeconomic theory are therefore inadequate for capturing the complexity, uncertainty, heterogeneity, and bounded rationality of human behavior (Filatova et al., 2011; Parker et al., 2003; Simon, 1955).

As a result, empirical approaches derived from comprehensive data have gained increasing attention in ABM research. Examples include participatory approaches and sample surveys that serve to model decision making (Matthews et al., 2007; Parker et al., 2003; Robinson et al., 2007). Such approaches are particularly promising in settings where agents may not strictly follow the principles of economic rationality. This behavior is prevalent in developing countries where farmers often face a number of simultaneous objectives and constraints that go beyond profit maximization principles, such as minimizing risks, satisfying auto-consumption requirements, and balancing labor skills and availability. Moreover, culture and traditions may play more important roles in land-use decisions, and information asymmetry may limit knowledge about market developments and technological advances. Participatory approaches more effectively account for multifaceted objectives and constraints by including stakeholders in the development and calibration of the model, which will enhance the decision-making component of ABMs (Matthews et al., 2007; Parker et al., 2003). Prominent examples of participatory methods include role-playing games that allow the incorporation of the hypothetical decisions of and interactions between agents in an ABM model (Bousquet et al., 2002; Castella et al., 2005). Yet, how to formulate and parameterize the mathematical models based on qualitative knowledge gained during the group discussion and how to effectively communicate with stakeholders remain key challenges. Another approach is to use survey data and microeconomic theory to parameterize and calibrate agents' behavioral models with quantitative data from individuals and households (Robinson et al., 2007). However, the snapshot-type data collected through questionnaires and the lack of direct involvement of stakeholders (unlike the participatory approach) precludes a comprehensive description of the complex and dynamic decision-making process.

To tackle these challenges in ABMs, we adopted Bayesian belief networks (BBNs) to simulate land-use decision making under uncertainty. BBNs encode probabilistic relationships among variables of interest with a graphical interface that provides a natural and intuitive way to model causal reasoning with a solid mathematical foundation (Heckerman et al., 1995; Jensen, 2002; Pearl, 2009). The advantages of using BBNs in land-use change simulations are multi-fold. First, the capability of knowledge representation and inference under conditions of uncertainty makes BBNs an appealing tool to represent individual reasoning in decision making. The probabilistic outcomes account for the variation inherent in parameter estimates and thus implicitly incorporate a risk component (Kinzig et al., 2003; Newton et al., 2007). The ability of BBNs to model causal connections between factors that shape land-use decisions is particularly valuable for our purposes because it allows us to draw inferences about the effects of land-use policies on local land-use outcomes. Second, BBNs can incorporate the qualitative beliefs and attitudes of stakeholders, so-called prior knowledge, along with quantitative data (Marcot et al., 2001; Newton et al., 2006). This feature allows modelers to parameterize and validate land-use decision making by combining qualitative information gained from participatory discussions and quantitative data collected, for example, in household surveys. BBNs can effectively facilitate focus group discussions via the graphical interface and the influence diagram, which support the active involvement of stakeholders in model calibration and validation. The influence diagrams are also relevant for decision makers because they are transparent, intuitive and easy to understand. Contrary to many other simulation models, stakeholders can be more readily involved in model and scenario development, which eases their skepticism towards the modeling exercise (Gilbert et al., 2002; Voinov and Bousquet, 2010). Compared to other graphical models, such as decision trees, BBNs have higher predictive performance and are better suited to capture the complexity of the underlying decision making (Janssens et al., 2004). In summary, the flexibility of BBNs in combining quantitative evidence with stakeholder information renders them an excellent extension to more rigid, rule-based expert systems that characterize an optimal production program.

BBNs and ABMs are complementary in land-use simulations because ABMs provide a natural framework for accommodating multiple agents and compensate for the deficiency in the spatial and temporal dimensions of BBNs. However, due to the technical and computational challenges in coupling the two approaches, few attempts at integrating BBNs and ABMs have been reported thus far. One exception is the MABEL model, implemented in the C/C++ programming languages, which loosely coupled BBNs and ABMs with Swarm in a distributed client/server architecture and was successfully applied for land-use change simulations (Alexandridis and Pijanowski, 2007; Lei et al., 2005).

Farmers make land-use decisions not only based on their socioeconomic characteristics and physical traits of their land, but they also learn from and follow other farmers' actions. In other words, farmers show contingent behavior in the process of adopting a policy or technology (Weisbuch, 2000). Much empirical evidence supports such a "bandwagon effect" because farmers frequently base their adoption decisions on information conveyed to them by their peers (Berger, 2001; Deffuant et al., 2002b, 2000), make decisions under the influence of social norms (Chen et al., 2012, 2009a), and sometimes simply imitate the land-use practices adopted by their peers (Gotts and Polhill, 2009). Additionally, the spatial autocorrelation and agglomeration patterns exhibited in land-use change often go beyond the clustered distribution of biophysical features of landscapes and are also characterized by social interactions among land managers (Verburg et al., 2004). Unfortunately, many land-use-change models fail to explicitly incorporate social behavior and interactions among land users despite the importance of peer influences on decision making and the adoption of policies and technologies (Buttel et al., 1990). The "soft" nature of social variables and the difficulty of measuring the associated parameters often discouraged the consideration of social

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