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Coupling human and natural systems: Simulating adaptive management agents in dynamically changing forest landscapes

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ABSTRACT

Global change poses considerable challenges for ecosystems and their managers. To address these challenges it is increasingly clear that a coupled human and natural systems perspective is needed. While this science has advanced greatly in recent years, its mainstreaming into operational ecosystem management has proven to be difficult. One aspect complicating the application of a coupled human and natural systems approach has been the lack of tools that are simultaneously able to accommodate the complexities of ecological and social systems. However, neglecting their full interactions and feedbacks could lead to either an overestimation of the systems' vulnerability to global change (e.g., where the social adaptive capacity is disregarded in assessments based solely on ecosystem models), or to the pretense of stability (e.g., where the dynamic responses of ecosystem processes to environmental changes are neglected in models of the social system). These issues are of particular importance in forest ecosystems, where human interventions affect ecosystem dynamics for decades to centuries. In order to improve the assessments of future forest trajectories, our objectives here were (i) to operationalize and describe the coupling of human and natural systems in the context of landscape-scale forest ecosystem management, and (ii) to demonstrate simulated interactions between the social and ecological spheres in the context of adaptation to a changing climate. We developed an agent-based model accounting for different spatial (stand and management unit) and temporal (operational and strategic) levels of forest management decision making and coupled it with the forest landscape simulator iLand. We show that the coupled human and natural systems model is autonomously able to reproduce meaningful trajectories of managed mountain forest landscape in Central Europe over the extended period of multiple centuries. Experimenting with different decision heuristics of managing agents suggests that both passive (reactive) and active (prospective) adaptive behavior might be necessary to successfully stabilize system trajectories under rapidly changing environmental conditions. Furthermore, investigating multi-agent landscapes we found that diversity in managerial responses to environmental changes increases the heterogeneity on the landscape, with positive effects on the temporal stability of ecosystem trajectories. We conclude that an integrated consideration of human and natural systems is important to realistically project trajectories of managed forests under global change, and highlight the potential of social–ecological feedbacks and heterogeneity in stabilizing the provisioning of ecosystem services in a changing environment.

1. Introduction

Ecosystems around the globe are increasingly under pressure from environmental changes, a loss of biological diversity, and rising societal demands on ecosystem services (Rockström et al., 2009). Climate change is expected to profoundly alter the composition, structure, and functioning of ecosystems, e.g., through a facilitation of disturbance events such as wildfires and bark beetle outbreaks (Seidl et al., 2014). Furthermore, changes in the global nitrogen cycle and the eutrophication resulting from excessive nitrogen input into ecosystems are increasingly threatening freshwater systems (Gruber and Galloway, 2008). Changes in climate alongside with land-use changes contribute to the ongoing loss of biological diversity (Butchart et al., 2010), and threaten to lead to drastic (and possibly irreversible) impacts on the earth system.

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To address these emerging challenges in the stewardship of our planet in general and in the management of ecosystems in particular the concept of resilience has been proposed recently (Biggs et al., 2012). In this context, resilience has been defined as the capacity of a system to retain desired structures, processes, and functions in the face of disturbance and change (Folke 2006; Liu et al., 2007). While the conceptual idea of resilience has been proposed already some decades ago (Holling, 1973) a key finding of more recent research was that an integrated consideration of social and ecological systems is required to understand and successfully address the complexities of global change and biodiversity loss in the stewardship of ecosystems (Liu et al., 2007). And while considerable advances have been made in recent years in developing a sound conceptual framework for such a coupled human and natural systems science (Biggs et al., 2012; Chapin et al., 2010), its mainstreaming into specific aspects of ecosystem management has proven to be challenging (see e.g., Spies et al., 2014).

Challenges are particularly profound in the context of forest ecosystems, where the effects of human interactions with the ecosystem prevail for decades to centuries, and a temporal decoupling between management decisions and their implications on a rapidly changing society can frequently be observed. One factor that is currently restricting a wider application of a coupled human and natural systems perspective in forest ecosystem management is the lack of appropriate tools for addressing the dynamic interactions between social and ecological systems over extended time horizons. A variety of models for simulating and projecting the dynamics of forest ecosystems have been presented and are being used to study the ecological responses to global change (Evans, 2012; Mäkelä et al., 2000). And while these models incorporate an increasing level of ecological process understanding, they frequently are limited in addressing the interactions of ecosystems with humans. This limitation arises *inter alia* from a scale mismatch between the typically considered entity in forest models (i.e., trees to stands) and the scale at which stewardship decisions are made and resilience can be assessed (i.e., the watershed, landscape, and beyond) (Seidl et al., 2013). Theory suggests that scales both above and below the focal scale need to be considered in order to assess and manage for resilience (Walker et al., 2004), yet most tools currently available are not able to accommodate such a multi-scale perspective. Furthermore, the overwhelming majority of forest models approximate human interaction with the biosphere in the form of static, pre-defined interventions. These can be prescriptions (i.e., which management action to implement where and when (e.g., Rasche et al., 2011)), or they can include a priori defined if-then rules to study alternative management scenarios (e.g., Seidl et al., 2011b). Most of these approaches do, however, fall short in embracing the complex and dynamic responses of managers to a changing environment.

This latter aspect is the domain of agent-based models (ABMs), i.e., a class of models that explicitly accounts for the fact that managerial decisions are an emerging property of the intentions, beliefs, and interactions between agents and their environment (An, 2012; Gilbert, 2007). ABMs have been applied widely in a variety of fields, e.g. in land use change modeling (Kelley and Evans, 2011), policy analysis (Smajgl and Bohensky, 2013), and value chain assessments (Schwab et al., 2009). Examples in the context of forest management include analyses on the influence of information flow between land managers (Satake et al., 2007) and the impact of social–ecological change on harvesting patterns (Leahy et al., 2013). While ABMs are a powerful means to capture the social dynamics of resource management decisions, they are often limited with regard to the representation of ecological processes. Frequently, the ecosystem trajectories underlying the simulated management decisions of agents assume static or unlimited resource supply, or are derived from empirical models (e.g., Bone and Dragićević, 2009; Kostadinov et al., 2014), rather than being based in ecological process understanding. Other ABM approaches have relied on detailed process models but used them to derive a predefined set of external inputs (e.g., Bolte et al., 2007; Gaube et al., 2009), limiting their application in the context of dynamically changing environmental conditions.

Recent efforts to bridge this gap between the ecological and social realms in modeling have been made in fields such as the dynamic simulation of land-use changes. (see e.g. Filatova et al., 2013; Schreinemachers and Berger, 2011). However, in the context of management decisions within a given land-use in general and forest ecosystem management in particular the dynamic coupling of human and natural systems remains a challenge for existing simulation approaches (Bousquet and Le Page, 2004; Filatova et al., 2013). Currently, this coupling remains a key limitation of our ability to make robust predictions on the adaptive capacity, and quantify their resilience to global change. Here, we address this issue by presenting an approach of how to couple a process-based forest landscape model with an agent-based model of forest management. Our specific objectives were (i) to operationalize and describe the coupling between human and natural systems in simulation, and (ii) to demonstrate the potential to simulate dynamic interactions between the social and ecological spheres in the context of a changing climate. In the following we will first briefly introduce the forest landscape model (natural system) and agent-based model (human system), and subsequently focus particularly on the intricacies of their coupling. Subsequently we will present three simulation exercises demonstrating the behavior of the coupled model for a multi-agent forest landscape under climate change.

2. Methods and materials

2.1. Natural system: the iLand model

The individual-based forest landscape and disturbance model iLand is a process-based ecosystem model that simulates forest landscape dynamics at the level of individual trees (Seidl et al., 2012). The competition of trees for resources is simulated spatially explicitly in iLand, using an approach rooted in ecological field theory. Resource utilization is modeled based on a light use efficiency approach accounting for atmospheric (suboptimal temperatures, humidity, CO_2 availability) and soil (nitrogen and water availability) constraints. Based on their resource availability individual trees are dynamically adapting their growth strategies to their environment. Trees can either die from age-dependent chance, stress from competition or environmental limitations, or a range of natural disturbance agents (such as wind and wildfire) in the model. Regeneration is modeled spatially explicit in the landscape, taking into account the availability and distribution of seeds, the species-specific climatic limitations for establishment, and the spatial distribution of resources such as light, water, and nutrients. The model was extensively tested and evaluated across a range of ecosystems on two continents in previous studies (Seidl et al., 2012; Silva Pedro et al., 2014). It is particularly well suited to serve as the ecosystem modeling platform for the current study as (i) its individual tree resolution allows the simulation of complex silvicultural activities (such as variable density thinning regimes), (ii) its process-based architecture ensures robust responses of ecosystem processes to changing environmental conditions, and (iii) its computational efficiency and open architecture allow for an efficient integration of complex models of the human system.