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Development of a stakeholder-driven spatial modeling framework for strategic landscape planning using Bayesian networks across two urban-rural gradients in Maine, USA

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ABSTRACT

Land use change results from frequent, independent actions by decision-makers working in isolation, often with a focus on a single land use. In order to develop integrated land use policies that encourage sustainable outcomes, scientists and practitioners must understand the specific drivers of land use change across mixed land use types and ownerships, and must consider the combined influences of biophysical, economic, and social factors that affect land use decisions. In this analysis of two large watersheds covering a total of 1.9 million hectares in Maine, USA, we co-developed with groups of stakeholders land use suitability models that integrated four land uses: economic development, ecosystem protection, forestry, and agriculture. We elicited stakeholder knowledge to: (1) identify generalized drivers of land use change; (2) construct Bayesian network models of suitability for each of the four land uses based on site-level factors that affect land use decisions; and (3) identify thresholds of suitability for each factor and give relative weights to each factor. We then applied 12 distinct Bayesian models using 99 spatially explicit, empirical socio-economic and biophysical datasets to predict spatially the suitability for each of our four land uses on a 30 m × 30 m pixel basis across 1.9 million hectares. We evaluated both the stakeholder engagement process and the land use suitability maps. Results demonstrated the potential efficacy of these models for strategic land use planning, but also revealed that trade-offs occur when stakeholder knowledge is used to augment limited empirical data. First, stakeholder-derived Bayesian land use models can provide decision-makers with relevant insights about the factors affecting land use change. Unfortunately, these models are not easily validated for predictive purposes. Second, integrating stakeholders throughout different phases of the modeling process provides a flexible framework for developing localized or generalizable land use models depending on the scope of stakeholder knowledge and available empirical data. The potential downside is that this can lead to more complex models than anticipated. The trade-offs between model rigor and relevance suggest an adaptive management approach to modeling is needed to improve the integration of stakeholder knowledge into robust land use models.

1. Introduction

A major goal of land use change research is to develop models for improving the ability to predict and to interpret the patterns and impacts of human development on natural landscapes across multiple ownership types and spatial scales. This information can help inform and guide land use planning and policy development to support desired outcomes in a region. In order to be most effective, land use change models should: (1) identify the specific drivers of land use change across mixed landscapes; (2) consider the combined influences of biophysical suitability, economic

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viability, and socio-political feasibility on future land use patterns; and (3) represent small-scale behaviors that underlie larger-scale patterns (Kok and Veldkamp, 2001; Verburg et al., 2002). This paper presents a stakeholder-driven modeling framework for identifying these specific drivers of local behaviors and evaluating the aggregated patterns across two large watersheds in Maine.

Worldwide, development pressures have spurred numerous land use studies to assess the vulnerability and susceptibility of different regions to various development pressures (Baker et al., 2004; Stein et al., 2005, 2009; Turner et al., 2007; Verburg et al., 2002). In particular, the U.S. Forest Service's Forests on the Edge studies (Stein et al., 2005, 2009; White et al., 2009) have sought to identify regions in the U.S. where urbanization is threatening forest cover and associated ecosystem services. Conservation planning has well-defined principles for protecting land from anthropogenic disturbances and other land use changes (Margules and Pressey, 2000; McDonald, 2009; Miller et al., 2009). However, those principles typically focus on designing systems that prevent development in order to protect biological integrity and ecosystem services (Newburn et al., 2005), thereby pitting development against ecosystem protection and/or natural resource management. As a result, such studies may provide little guidance for decision-makers seeking to balance conservation with socio-political and economic objectives. A major challenge is to evaluate simultaneously the suitability of a heterogeneous landscape for development, ecosystem protection, and natural resource management in order to identify combinations that meet demands for multiple land uses. Attaining such a holistic approach is difficult given the diversity of stakeholders and the wide range of behaviors governing the interactions of social, economic, and ecological drivers of different land uses.

1.1. Stakeholder involvement in decision support for land use planning

Despite the growing inclusion of stakeholders in land use planning efforts (Steiner, 1990), a disconnect remains between the ability of planners to develop well-designed land use plans and the ability of policy-makers, regulators, and citizens to implement such plans (Knight et al., 2008; te Brömmelstroet, 2009). To bridge this gap, scientists and practitioners must derive planning tools that are credible, salient, and legitimate in the eyes of decision-makers (Cash et al., 2003) and useful to practitioners (te Brömmelstroet, 2009). Incorporating stakeholder knowledge into land use analyses lends credibility and relevance, and may create critical buy-in which can help mitigate distrust and resistance during plan implementation (Gray et al., 2012; Krueger et al., 2012; Voinov and Bousquet, 2010). Often what is ideal from a planning perspective does not meet the needs of individual decision makers (e.g., landowners). For instance, Downs (2005) showed that even though Smart Growth principles have strong appeal in theory, they often fail to be implemented because of a disconnect between what is desirable at a large scale, and the willingness of individuals to make small-scale decisions to achieve those outcomes.

Martin et al. (2012) reviewed the status of efforts to integrate expert knowledge with conservation science, and cited problems of complexity, limited data, and the time-sensitive nature of decision-making as key reasons to include experts. These reasons are also relevant to land use planning, which often suffers from similar challenges. Land use planning relies heavily on complex interactions among actors, economic incentives, regulations, and biophysical characteristics of the landscape. Martin et al. (2012) argued for rigorous, scientific methods of eliciting expert knowledge, and provided a set of best practices, including gathering both uncertainty and best estimates together, identifying a method of weighting and combining judgments, and providing feedback to experts throughout the process.

Others have addressed the difficulties of integrating expert knowledge in modeling processes (Krueger et al., 2012; Martin et al., 2012; O'Hagan, 2012; Price et al., 2012; Voinov and Bousquet, 2010). For example, Krueger et al. (2012) provided a typology of expert-based models used in environmental modeling, and suggested objective ways to integrate expert opinion throughout multiple phases of modeling. Voinov and Bousquet (2010) argued that despite the challenges and uncertainty associated with using stakeholders in model development, including them is important for developing models that can inform and influence land use decisions.

In this study, we distinguish between *experts* and *stakeholders*, where the former provide either substantive, normative, or adaptive knowledge (Martin et al., 2012), and the latter offer not only one of those, but also have influence either directly or indirectly over a particular process (e.g., practitioners such as real estate developers, city planners or forest managers). The literature is replete with studies that use *experts* (e.g., Verburg et al., 2002), but relatively few that engage *stakeholders* in model development (Hulse et al., 2004; Krueger et al., 2012; Price et al., 2012), where the difference is that experts are typically scientific thought leaders removed from decision-making while stakeholders may not hold the same theoretical knowledge as experts but are actively engaged in land use decisions. Hulse et al. (2004) found that outputs derived from scenarios based exclusively on expert opinion often lack political plausibility, while those developed only with stakeholders are difficult to quantify statistically. Scott (2011) cautioned against relying on stakeholders who have only weak connections to policy development because they may reduce the relevance otherwise gained by including stakeholders. In this study, we relied on both scientific experts and stakeholders engaged in decision-making.

We also distinguish between models that incorporate expert and/or stakeholder knowledge at one point in the modeling process, versus those that use it in multiple stages of the model development process. For instance, some investigators have used expert (or stakeholder) knowledge to evaluate models structured and/or parameterized *a priori* by the research team (Beier et al., 2011; McCloskey et al., 2011). In contrast, other models have been co-developed by experts (or stakeholders) during multiple (e.g., Swetnam et al., 2011), or even all phases of the modeling process (e.g., Price et al., 2012), including model specification, parameterization, and evaluation. As research partners, stakeholders have a role in evaluating model validity, particularly for studies that project land change into the future where empirical data are often limited (Celio et al., 2012; Marcot, 2012; Parker et al., 2003).

1.2. Bayesian networks and land use suitability

Bayesian networks (BNs) are decision support tools that use Bayes' probability theory to describe decision processes by estimating the joint probability of an outcome based on prior information about input factors (Marcot et al., 2006). The flexibility of BNs allows researchers to supplement limited empirical data with expert knowledge, or in some cases where no empirical data are available, the expert opinion supplants empirical data. BNs have roots in the fields of artificial intelligence (Charniak, 1991) and medical research (Spiegelhalter et al., 2013), but are now commonly used in environmental sciences (Marcot, 2012). For instance, BNs have been used to estimate habitat suitability (e.g., Smith et al., 2007), and have recently been employed in land use planning (e.g., Kocabas and Dragicevic, 2007).

A BN consists of an influence diagram that describes underlying behaviors in a process, and estimates the probability of an outcome as expressed by a posterior probability distribution (PPD).