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From meta-studies to modeling: Using synthesis knowledge to build broadly applicable process-based land change models

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A B S T R A C T

This paper explores how meta-studies can support the development of process-based land change models (LCMs) that can be applied across locations and scales. We describe a multi-step framework for model development and provide descriptions and examples of how meta-studies can be used in each step. We conclude that meta-studies best support the conceptualization and experimentation phases of the model development cycle, but cannot typically provide full model parameterizations. Moreover, meta-studies are particularly useful for developing agent-based LCMs that can be applied across a wide range of contexts, locations, and/or scales, because meta-studies provide both quantitative and qualitative data needed to derive agent behaviors more readily than from case study or aggregate data sources alone. Recent land change synthesis studies provide sufficient topical breadth and depth to support the development of broadly applicable process-based LCMs, as well as the potential to accelerate the production of generalized knowledge through model-driven synthesis.

1. Introduction

Human modification of the natural landscape through land use is a complex and multi-dimensional process that requires insights from a wide range of scientific disciplines to understand and predict. Land use is the direct result of human decision-making and as such has a wide variety of causes, ranging from factors at the level of individual land-users to the regional and global settings in which local land-use decisions are embedded (Lambin and Meyfroidt, 2011). The consequences of land use are equally as varied and concern processes such as food production, biodiversity

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preservation, and carbon storage, all with impacts on ecosystems and human well-being (Rindfuss et al., 2008; Verburg et al., 2013a). Given this complexity, the land change science (LCS) community, which encompasses both land-use and land-cover change research, has identified two major challenges: "(1) improving our understanding of the complex feedbacks between the societal and environmental components of the integrated land system, and (2) up-scaling of local and regional process understanding to achieve global process understanding" (GLP, 2005; Rounsevell et al., 2012: 900). Numerous disciplinary approaches and analytical tools have been used to study land-use and land-cover change, but integration between two approaches in particular – synthesis research (e.g., meta-studies) and process-based modeling – has the potential to address both of the above challenges.

Land change models (LCM) are frequently used as tools to improve our understanding of land systems through historic analyses of land-use and land-cover change (referred to as 'land change' from hereafter), or ex-ante assessments of policy options (Brown et al., 2013; NRC, 2013). While some models adopt a pattern-based approach (i.e. aim to describe changes in observed land change patterns using statistical, machine learning, or comparable approaches), an increasing number of models use a process-based approach (i.e. aim to represent the mechanisms through which land change patterns are produced). General classes of process-based LCMs include sector-based (e.g., Hertel et al., 2009) and spatially disaggregated economic models (e.g., Irwin and Bockstael, 2002) and agent-based models, which tend to include more social science data than pattern-based LCM approaches (NRC, 2013). As human decision-making is fundamental to land change, process-based LCMs are critical for developing a causal understanding of the behavior of land-change agents in response to changing environmental, economic, or institutional conditions, and the feedbacks that such behavioral responses may create (NRC, 2013; Rindfuss et al., 2007).

However, empirically-grounded models of human decision-making processes often have high data demands throughout the iterative model development process (Messina et al., 2008; van der Leeuw, 2004; van Vliet et al., 2011), and such data can span biophysical and social realms and multiple spatial and temporal scales in order to adequately capture all the factors that influence decision-making (Janssen and Ostrom, 2006; NRC, 2013; Robinson et al., 2007). Place-based case study research has traditionally been an important source of data and knowledge for process-based LCMs. Case studies consistently integrate biophysical, socio-economic, cultural, and/or institutional elements and their links to observed land changes, and are thus the standard for causal explanations in land change research (Rindfuss et al., 2007; Rounsevell et al., 2014). Process-based LCMs that leverage the rich empirical traditions of land change case study research (e.g., Houet et al., 2010; Robinson et al., 2007; Valbuena et al., 2010a) are well suited to understand human–environmental interactions and feedbacks, and thus address the first major challenge for the LCS community.

While the deductive nature of process-based models is well suited to the second challenge to the LCS community (Overmars et al., 2007) – to scale-up local and regional to global process understanding – process-based LCM built from case studies are, by definition, location specific. This is due in part to the tendency for case studies to investigate the local contextual conditions that may not be easily generalized and valid at broader scales or coarser resolutions of analysis. Regional or global scale LCMs must then abstract from heterogeneous, local-scale processes, such as land-use decision-making, based on simplistic theoretical concepts such as profit optimization or expert-based decision rules that directly relate land use choices to land or climate suitability (Bamière et al., 2011; Gusdorf and Hallegatte, 2007; Rounsevell et al., 2014). Both approaches lack adequate representation of the huge spatial and temporal diversity of human behavior and decision processes, resulting in biases towards particular land change decision assumptions or contexts (e.g., market-driven), overly focused on variables only available from regional or national-level census products, poorly validated, and/or regarded as highly uncertain (Verburg et al., 2013b). In order to create process-based models that can *also* scale-up local insights to broader scales, such models must be designed, parameterized, and tested with data and causal explanations synthesized from many local observations to ensure broader applicability at regional and global scales.

As a synthesis research method, *meta-studies* have potential to overcome the challenges of scaling-up placed-based insights to regional or global scales when integrated into the model development process. *Synthesis* is a research approach that draws upon and distills many sources of data, ideas, explanations, and methods in order to accelerate knowledge production beyond that of less integrative approaches (see 'synthesis' at http://sesync.org/glossary/). *Meta-studies* are a sub-group of synthesis methods that are distinct from literature reviews, analytical review methods, and fully quantitative synthesis methods because they (a) conduct analyses across prior case studies of a common phenomenon as the observational unit (Rudel, 2008), and (b) possess systematic case selection criteria intended to produce a comprehensive and comparable collection of cases (see Magliocca et al., 2015 for details). Conducting a land change meta-study generally involves the steps of: 1) comprehensive case study search, 2) systematic case selection, 3) synthesis of explanatory frameworks presented by case study authors, 4) statistical analysis of quantitative and/or coded qualitative data reported in case studies, and 5) identification and interpretation of commonalities and differences in the causes and/or consequences of land change. To avoid confusion with the more common parlance of *meta-analysis*, we adopt the distinction presented in Magliocca et al. (2015) which defines *meta-analysis* as a special case of meta-study that utilizes more standardized and explicit methodologies to statistically compare parameter values and their variance within and across systematically selected case studies.

In land change science, meta-studies compare local variations in a particular land change phenomenon and investigate the drivers and/or impacts of that change to discern broader-scale patterns and explanations, and thus contextualize the relative scope and generalizability of the land change under study. Land change meta-studies tend to either analyze the processes that contribute to (i.e., cause) the observed change or the processes that the land change influences (i.e., consequence), although there are exceptions that study both (e.g., Cramb et al., 2009; Kendal et al., 2012). To date, most land change meta-studies have focused on the consequences of land change (Magliocca et al., 2015). A meta-study of synthesis methods in land change science was conducted by Magliocca et al. (2015) and found that out of the 181 studies analyzed only 27 were explicitly used to inform modeling efforts, and of those only five used meta-study techniques. More importantly, all five of these meta-studies analyzed the consequences rather than the causes of land change.

These five meta-studies covered a wide range of land change consequences. Seto et al. (2011) performed a cross-site meta-data-analysis of 326 case studies reporting remotely sensed extents of urban land cover change, which was used to formulate a statistical model to predict future urban expansion based on variables such as GDP and population growth. Schueler et al. (2009) conducted a meta-analysis of 65 studies that reported the effects of impervious surface cover on urban stream degradation, and their findings were