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Spatial modeling of agricultural land use change at global scale

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ABSTRACT

Long-term modeling of agricultural land use is central in global scale assessments of climate change, food security, biodiversity, and climate adaptation and mitigation policies. We present a global-scale dynamic land use allocation model and show that it can reproduce the broad spatial features of the past 100 years of evolution of cropland and pastureland patterns. The modeling approach integrates economic theory, observed land use history, and data on both socioeconomic and biophysical determinants of land use change, and estimates relationships using long-term historical data, thereby making it suitable for long-term projections. The underlying economic motivation is maximization of expected profits by hypothesized landowners within each grid cell. The model predicts fractional land use for cropland and pastureland within each grid cell based on socioeconomic and biophysical driving factors that change with time. The model explicitly incorporates the following key features: (1) land use competition, (2) spatial heterogeneity in the nature of driving factors across geographic regions, (3) spatial heterogeneity in the relative importance of driving factors and previous land use patterns in determining land use allocation, and (4) spatial and temporal autocorrelation in land use patterns.

We show that land use allocation approaches based solely on previous land use history (but disregarding the impact of driving factors), or those accounting for both land use history and driving factors by mechanistically fitting models for the spatial processes of land use change do not reproduce well long-term historical land use patterns. With an example application to the terrestrial carbon cycle, we show that such inaccuracies in land use allocation can translate into significant implications for global environmental assessments. The modeling approach and its evaluation provide an example that can be useful to the land use, Integrated Assessment, and the Earth system modeling communities.

1. Introduction

Changes in land use are driven by non-linear interactions between socioeconomic conditions (e.g. population, technology, and economy), biophysical characteristics of the land (e.g. soil, topography, and climate), and land use history (Lambin et al., 2001, 2003). The spatial heterogeneity in driving factors has led to spatially distinct land use patterns. Land use change models exploit techniques to understand the spatial relationship between historical changes in land use and its driving factors (or proxies for them). Such models are also used to project spatial changes in land use based on scenarios of changes in its drivers. The importance of land use change models is evident from the wide range of existing modeling approaches and applications (see reviews by NRC, 2014; Heistermann et al., 2006; Verburg et al., 2004; Parker et al., 2003; Agarwal et al., 2002; Irwin and Geoghegan, 2001; Briassoulis, 2000; U.S. EPA, 2000). However, most land use change models are designed for local to regional scale studies (typically sub-national to national level); global-scale modeling approaches are scarce (Rounsevell and Arneth, 2011; Heistermann et al., 2006).

Global-scale land use modeling is challenging compared to smaller-scale approaches for three main reasons. First, the set of driving factors and their spatial characteristics of change are diverse across the globe, and models need to represent this variability (van Asselen and Verburg, 2012). Second, the various factors that affect land use decisions operate at different spatial scales. For example, landowners make decisions at local scale, whereas factors like governance, institutions, and enforcement of property rights operate at much larger scales. Ideally, global-scale models should incorporate the effects of driving factors at multiple scales (Rounsevell et al.,

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2014; Heistermann et al., 2006). However, an integrated understanding of how the multi-scale drivers combine to cause land use change is far from complete (Lambin et al., 2001; Meyfroidt, 2013). Third, spatially and temporally consistent data for many important driving factors (e.g. market influence) are not readily available at a global scale and at the required spatial resolution (Verburg et al., 2011, 2013).

Despite these challenges, there are three reasons for modeling land use at a global scale. First, several key drivers of land use (e.g. climate) and their impacts on land use have no regional demarcations and substantial feedback exists between them (Rounsevell et al., 2014). Addressing the feedback between land use and socioecological systems requires a globally consistent framework. Second, regions across the world are interconnected through global markets and trade that can shift supply responses to demands for land across geopolitical regions (Meyfroidt et al., 2013). Modeling such complex interactions among economies demands a global scale approach. Third, the aggregate consequences of land use at the global scale have significant consequences for climate change (Pielke et al., 2011), global biogeochemical cycles (Jain et al., 2013), water resources (Bennett et al., 2001) and biodiversity (Phalan et al., 2011), making global land use modeling a useful component of analyses of these issues.

These reasons have motivated global scale assessments using Integrated Assessment Models (IAMs) that seek to treat the interactions between land and other socioecological systems in a fully coupled manner (Sarofim and Reilly, 2011). In IAMs, socioeconomic models are coupled with biophysical models (process-based vegetation models and/or climate models) to translate socioeconomic scenarios into changes in land cover and its impacts on environmental variables of interest (van Vuuren et al., 2012). IAMs typically disaggregate the world into 14–24 regions (van Vuuren et al., 2011), and land use decisions are made at this regional scale. Some IAMs have spatially explicit biophysical components, and in these cases land use information on geographic grids at a much higher spatial resolution is required (typically $0.5^\circ \times 0.5^\circ$ lat/long). To provide this information, spatial land use allocation approaches are employed to downscale aggregate land demands for large world regions to individual grid cells. Examples of such global scale land use allocation approaches can be found in the Global Forest Model (Rokityanskiy et al., 2007), IMAGE (Bouwman et al., 2006), MagPie (Lotze-Campen et al., 2010), KLUM (Ronneberger et al., 2005, 2009), MIT-IGSM (Reilly et al., 2012; Wang, 2008), GLOBIO3 (Alkemade et al., 2009), GLOBIOM (Havlik et al., 2011), Nexus land use model (Souty et al., 2012, 2013), and the Global Land use Model (GLM) (Hurtt et al., 2011).

In this article, we develop a new global land use allocation model specifically to downscale agricultural (cropland and pastureland) land use from large world regions to the grid cell level. Agricultural land use merits special attention because it is associated with the majority of land use-related environmental consequences (Green et al., 2005), currently occupying ~40% of Earth's land area (Foley et al., 2005). There are two novel features of our approach that distinguish it from previous approaches.

First, our model predicts fractional land use within each grid cell (continuous field approach) driven by time-varying socioeconomic and biophysical factors. In contrast, most existing models do one or the other but not both. For example, many downscaling methods represent land use in each grid cell ($0.5^\circ \times 0.5^\circ$ lat/long or coarser) by the dominant land cover category (e.g. MagPie, IMAGE, GLOBIOM, and the Nexus land use model). This simplified representation in land cover underestimates land cover heterogeneity and is a major source of uncertainty in impact assessments (Verburg et al., 2013). Some recent efforts (e.g. Letourneau et al., 2012; Schaldach et al., 2011) have addressed this problem by increasing spatial resolution, for example using 5-min grid cells that represent dominant land cover types. While such approaches are an improvement, they are also much more computationally intensive and do not escape the problem that for many variables representing land use drivers, high resolution data at the global scale are unavailable (Verburg et al., 2013). In other approaches (e.g., GLOBIO3 and GLM) land cover is represented as fractional units within each grid cell (again $0.5^\circ \times 0.5^\circ$ lat/long), but the approach to allocation is overly simplified, proportionally allocating land use projections for aggregate regions to grid cells as closely as possible to existing land use patterns. Such an approach does not account for the effect of changes over time in land use drivers, which can lead to land use projections that are inconsistent with those drivers (as will be shown later).

Second, we carry out the first global scale evaluation of a spatial land use allocation model over a long historical period (>100 years), reproducing the broad spatial features of the long-term evolution of agricultural land use patterns. Evaluation of global-scale spatial land use models is important because they are used to generate scenarios for 50–100 years into the future, for example, to explore issues related to greenhouse gas emissions and mitigation possibilities (Moss et al., 2010; Kindermann et al., 2008), climate change impacts on ecosystems (MEA, 2005; UNEP, 2012), biodiversity (TEEB, 2010; Pereira et al., 2010), or adaptation options involving land use (OECD, 2012; Phalan et al., 2011). While evaluation of model performance over the past 100 years is no guarantee of good performance over the next 100 years, demonstrating the ability of a model to reproduce long-term historical patterns increases confidence in its suitability for application to long-term scenarios of future change. The model evaluation presented here could serve as an example for how evaluation of other downscaling methodologies could be carried out (O'Neill and Verburg, 2012; Hibbard et al., 2010).

2. Methods and data

2.1. Overview of the approach

Our land use allocation model simulates the spatial and temporal development of cropland and pastureland at a spatial resolution of $0.5^\circ \times 0.5^\circ$ lat/long and at an annual time-step. The model operates at two different spatial levels. On the regional level, the aggregate regional demand for cropland and pastureland is provided as input to the model. The model then allocates this demand to individual grid cells within that region. We use a constrained optimization technique to allocate a fraction of each grid cell to cropland and pastureland while meeting the aggregate regional demand for each type of land. The optimization technique selects the most profitable land to grow crops and pasture based on (1) the suitability of each grid cell for crop or pasture production, determined by a set of 46 biophysical and socioeconomic factors (Table 1), (2) historical land use patterns (temporal autocorrelation) and (3) the land use predicted for neighboring grid cells (spatial autocorrelation).

A primary intended application of this model is as one component of a larger modeling framework that includes a global, regionally resolved economic model that generates scenarios of future demand for land at the regional level, similar to the approach taken in other IAMs or land use models as discussed above. However, the main aim of this paper is to present and evaluate our model in a historical simulation against 20th century gridded data of cropland and pastureland. Ideally, the model should be evaluated against observational data. However, purely observational data for global, spatially resolved land use data do not exist. Rather, existing gridded land use reconstructions are modeled estimates that draw on national and sub-national data to the extent possible (see Appendix A). For practical purposes, we assume existing land use