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Research Paper

A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects

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ABSTRACT

Land use and land cover change (LUCC) simulation models are effective and reproducible tools for analyzing both the causes and consequences of future landscape dynamics under various scenarios. Current simulation models primarily focus on the evolution of specific land use types under the influence of human activities, but they rarely consider background climatic effects. However, these background climate changes significantly affect the landscape dynamics and should be incorporated into long-term LUCC simulations under various human-climate-included scenarios. In this paper, we propose a future land use simulation (FLUS) model that explicitly simulates the long-term spatial trajectories of multiple LUCCs. The top-down system dynamics and bottom-up cellular automata were interactively coupled during the projection period, which improved the model's ability to accurately simulate future land use patterns. A self-adaptive inertia and competition mechanism was developed within the CA model to process the complex competitions and interactions between the different land use types. The proposed model was applied to an LUCC simulation in China from 2000 to 2010. The results show promising grid-to-grid agreement compared to actual land use, and the simulation accuracy is higher than other well-accepted models, such as CLUE-S and CA models. The model was further applied to the simulation of four scenarios from 2010 to 2050 that depict different development strategies by considering various socio-economic and natural climatic factors. The simulation results and findings demonstrate that the proposed model is effective for future LUCC simulation under variously designed scenarios. FLUS is available for free download at http://www.geosimulation.cn/FLUS.html.

1. Introduction

The land cover on earth and its anthropogenic exploitation are crucial links between human activities and the natural environment. Since the industrial era, land use and land cover change (LUCC) has been critical in contributing to regional and global climate change by driving energy recycling and material exchange on the land surface (Foley et al., 2005). Human-involved LUCCs, such as forest over-exploitation, agricultural intensification and urbanization, not only accelerate global warming via increasing greenhouse gas emissions (Kalnay & Cai, 2003; Pielke et al., 2002) but also pervasively cause irreversible biological diversity losses across the globe (Matson, Parton, Power, & Swift, 1997; Tilman et al., 2001; Vitousek, Mooney, Lubchenco, & Melillo, 1997). Rapid urban expansion and socio-economic development have increased the tension in human-environment interactions (Vitousek et al., 1997; Yao et al., 2016), as more than 50% of the world's population lived in urban areas in 2007, a number that will likely reach approximately 70% by 2050 (Bloom, 2011).

Spatiotemporal LUCC simulations are effective and reproducible tools for analyzing both the causes and consequences of alternative future landscape dynamics relative to socio-economic and natural environmental driving forces (Costanza & Ruth, 1998; Verburg, Schot, Dijst, & Veldkamp, 2004). The complex structure of linkages and feedback is expected to be solved using simulation models to project future land use trajectories and support future land-use policy decisions (Heistermann, Müller, & Ronneberger, 2006; Kline, Moses, Lettman, & Azuma, 2007; Schulp, Nabuurs, & Verburg, 2008). Cellular automata (CA) are common methods to simulate the LUCC spatial

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evolution by estimating the state of a pixel according to its initial state, the surrounding neighborhood effects and a set of transition rules. Although very simple, a CA model can generate rich patterns and can effectively represent nonlinear spatially stochastic LUCC processes (Batty, Couclelis, & Eichen, 1997). In the last two decades, a growing body of literature has described the applications of CA models in urban development studies (Clarke & Gaydos, 1998; Li and Yeh, 2000,2002; Li, Chen, Liu, Li, & He, 2011; White, Engelen, & Uljee, 1997; Wu, 1999). By properly defining the transition rules, urban CA models have strong capabilities for simulating the spatiotemporal complexities of urban systems (Chen, Li, Wang, & Liu, 2012; Li, Lin, Chen, Liu, & Ai, 2013; Liu & Hu et al., 2017; Liu, Li, Liu, He, & Ai, 2008; Liu, Li, Shi, Wu, & Liu, 2008; Liu, Li, Shi, Zhang, & Chen, 2010; Liu et al., 2014). Other studies have focused on simulating deforestation under the influences of natural hazards or human activities (Gustafson, Shifley, Mladenoff, Nimerfro, & He, 2000; Kok & Winograd, 2002). However, most of these models can only simulate the dynamics of one individual land use, while in many cases, different LUCC processes occur simultaneously and affect each other. Thus, multiple LUCC simulations are much more effective for determining realistic future land use patterns. Conducting multiple LUCC simulations within one CA model is challenging because of the interaction and competition among different land uses, which inevitably leads to very complicated definitions of the transition rules. The complicated interactions and competition among different land use types are not well explored. Most current studies simply estimate the probabilities of individual land use types separately and assign the highest value to the land grid, such as the ANN-CA (Li & Yeh, 2002) and CLUE-S series models (Verburg et al., 2002; Verburg & Overmars, 2009). Moreover, the role of climate change in long-term land use patterns is not well addressed in these models.

Climate change (global warming, extreme weather events, etc.) and ecological degradation (hydrological variation, soil erosion, etc.) have long-term effects that alter the natural landscape dynamics (Bakker et al., 2005; Geist & Lambin, 2004; Lambin, Geist, & Lepers, 2003; Li, Guangzhao, Xiaoping, & Xun, 2017; Okin, Murray, & Schlesinger, 2001). Temperature variability, freshwater availability and soil quality affect various human-dominated land use decisions, such as the redistribution and transformation of cultivated land, grassland and pastureland (Mendelsohn & Dinar, 1999; Wolf, Bindraban, Luijten, & Vleeshouwers, 2003). Such interactions and feedback within the LUCC environmental system will eventually have profound impacts on human welfare and long-term social sustainability through air pollution, natural resource shortages, food risk, etc. (Hansen, 2010; Hay & Mimura, 2006). Issues such as land degradation (De Koning, Verburg, Veldkamp, & Fresco, 1999), biodiversity (Chapin et al., 2000; Sala et al., 2000) and global climate change (Tangen, 1999) have increasingly demanded quantitative information on regional and global LUCCs and their future changes, both spatially and temporally. The exploration of both the LUCC natural environmental and anthropogenic impacts is vitally important for climate change adaptation and maintaining a sustainable landscape.

Another challenge of multiple LUCC simulations is that CA models are bottom-up models that determine the system evolution from a local perspective. However, macro-scale demands, political planning and background climate influences on different land use types cannot be properly represented in the traditional CA models (Ward, Murray, & Phinn, 2000). Thus, it is necessary to introduce top-down models to address these planning and development factors, such that demands for different use types can be determined from the macro-scale perspective and can be regarded as scenarios that represent future development pathways (Sohl, Sayler, Drummond, & Loveland, 2007; Xiang & Clarke, 2016). Through such coupling, the land use change quantities can be rationally determined. Subsequently, the CA model iterates and allocates these land use change quantities according to the transition rules at the local level. A series of researchers have proposed models to integrate the top-down quantitative estimation methods, such as historical trend extrapolation, complex multi-sector models (Verburg & Overmars, 2009), Forrester models (Berling-Wolff & Wu, 2004), and system dynamics (He et al., 2005; Huang, He, Liu, & Shi, 2014), using the bottom-up CA model to better simulate the LUCC dynamics. These top-down methods are designed to address the demands, planning, and developments of individual land use types from a macro-scale perspective to determine the land use change quantities. The CA model then allocates these land use change quantities through local interactions and evolutions of different land use types at the grid cell level. Examples of such integrated CA models include CLUE-S (Verburg et al., 2002), LTM (Pijanowski, Alexandridis, & Mueller, 2006), the SLEUTH model (Dietzel & Clarke, 2007), and FORE-SCE (Sohl et al., 2007). However, problems still occur, because these coupled models directly link two sub-models via the land use demands at the end of the study period, despite the bottom-up and top-down models being built using different assumptions. The interactions and feedback loops between the bottom-up and top-down models are ignored, leading to the separation of the macro land use demand projections and the local change allocations.

Although many of these models have addressed socio-economic and geographic condition factors, few studies have considered the background climate conditions. Many previous studies (Bakker et al., 2005; Mendelsohn & Dinar, 1999; Wolf et al., 2003) have agreed that climate factors (e.g., temperature increases and precipitation variations) have significant effects on specific LUCCs, such as forest, farmland, and pastureland. Without incorporating climate change scenarios, these models are not applicable for future LUCC simulations under human-climate-included scenarios and are therefore unable to reliably determine future land use patterns due to the significant effects of climate change on the LUCC dynamics. In addition, the top-down and bottom-up models are typically built upon different assumptions. Current simulation models typically loosely integrate two sub-models via the land use demands at the end of the study period, but they seldom consider their interactions and feedback, leading to the separation of the macro land use demand projection and the local change allocation. To summarize, although great progress has been achieved, three limitations exist in the current multiple LUCC simulation models: 1) Although the socio-economic factors and geographic conditions are well addressed, few studies have considered the background climate conditions. Future climate changes will have significant impacts on the long-term land use dynamics. 2) Most of the multiple LUCC models train and estimate the conversion probabilities of each land use type independently, resulting in a separation between the different land use types. The competition and interactions are not well explored in these models. Finally, 3) the interactions and feedback between the top-down and bottom-up models are not typically coupled, which results in the separation between the macro land use demand projection and the local change allocation.

In this paper, we present an approach that interactively integrates top-down system dynamics (SD) with a bottom-up CA model for a multiple LUCC dynamic simulation. The proposed integrated model differs from existing models in its ability to explicitly simulate the spatial trajectories of multiple LUCCs under alternative scenarios by coupling both human-related and natural environmental effects using an elaborate design of the interactions and competition among different land use types and using an interactive coupling mechanism between the SD and CA models. In the proposed model, we incorporated natural factors, including future global warming and precipitation variations and socio-economic developments into both the SD and CA models. A self-adaptive inertia and competition mechanism is designed to address the complex local land use interactions and estimate the transition probabilities of different land use types simultaneously. An "interactive coupling" mechanism is introduced into the model allocation, which integrates the bottom-up and top-down models interactively via the mutual feedbacks between land use quantities and local allocations along the entire simulated time series. This new coupling mechanism enables the two sub-models to evolve collaboratively. The proposed