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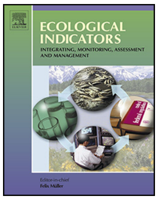

Simulation of urban expansion and encroachment using cellular automata and multi-agent system model—A case study of Tianjin metropolitan region, China

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ABSTRACT

The combination model of cellular automata and multi-agent system were used in this paper for simulating spatio-temporal dynamics of urban expansion and its encroachment on other lands at the regional scale. The human system(contain authorities and residents) and their behavior, the landscape system and its behavior as well as the inter actions between them were all simulated in this paper. The behavior of human system is established based on multi-agent system, the authority agent and the resident agent were both regarded as abstract entities. The cellular automata is embedded into the model for simulating the spontaneous urban growth. The impact of neighbor cells were considered so that the expansion of urban lands can be limited near the existed urban lands. Moreover, the rural residential lands have higher probability to convert to urban lands if they were close to the cities or towns. Simulation of urban expansion is undertaken on the time series from 2000 to 2020 for Tianjin metropolitan region, the largest open coastal city in northern China. The results show that Tianjin's urban lands focus on the epitaxial expansion around the central city accompanied with the growing exurb expansion distributing in multiple districts and counties. The croplands are taken the most area of the land-use types, 1764.03 km^2 are converted to urban lands, and more than one fourth of the rural residential lands are changed to urban lands in 2000–2020. The urban development and the cropland protection should be both taken into account to minimize the threats on food security and ecological environment.

1. Introduction

Land use and cover change (LUCC) has been widely acknowledged as one of the most profoundly human-induced impacts on the Earth's ecosystem (Vitousek et al., 1997). The causes, processes and consequences of LUCC as well as the interactions between human activities and land-use systems are identified as two of the core research topics in landscape ecology (Wu and Hobbs, 2002). Urbanization is arguably the most critical process and dramatic form of LUCC (Matthew and Wu, 2002; Reginster and Rounsevell, 2006). Urban lands account for only a small proportion of the Earth's land surface, but sufficient evidences indicate that urban expansion has inevitably brought about various effects on biodiversity, climate change, biogeochemical cycles and hydrological cycles at a wide range of scales (Lambin and Geist, 2001; Foley et al., 2005; Turner et al., 2007). Conversion from agricultural lands to urban lands represent the major land-use change of urbanization (Pickett et al., 2001; Bürgi et al., 2004), which has posed enormous pressure on cropland resources. Therefore, it is well worth exploring spatio-temporal dynamics of urban expansion, which aims at providing strategic decision for promoting sustainable urban development (Wu and David, 2002; Wu, 2008; Tian et al., 2011).

A variety of methods based on non-equilibrium and non-linear systems have been extensively introduced and exploited to simulate urban dynamics since the 1960s (Xu et al., 2007), such as percolation theory (Franceschetti et al., 2000), self-organization theory (Portugali, 2000) and cellular automata (Berling-Wolff and Wu, 2004). These approaches provide an insightful understanding

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of the driving forces and causal mechanisms of urban growth. However, modeling of LUCC involves the complexity of not only natural constraints but also human drivers (Le et al., 2008), while past generations of simulation models tend to ignore the explicit roles of human actors and fail to incorporate their diverse actions and decisions into modeling of urban landscape dynamics (Andersson et al., 2002; Veldkamp and Verburg, 2004).

Until the 1990s, academia gradually raised the cognition of the importance of coupled human-environmental systems (Stern, 1993). To better understand the multifaceted complexity of interactions among various components of coupled human-environmental systems, a new approach in land-use modeling community have emerged and become prevalent in the last decades (Torrens, 2001). In the context of agent-based modeling (ABM), the coupled human-environmental system is represented as self-organized agents who have specifically substantive states, structures and mechanisms (Le et al., 2008). Agent classes can be divided into physical, human or abstract entities, and their interactions have direct behavior or indirect reactions under response mechanisms (Fontaine and Rounsevell, 2009). Sub-models of various socio-ecological processes can be incorporated into agents' profile (Le et al., 2008), which allows human behavior on land-use to be captured in an explicitly mechanistic way (Matthews et al., 2007). It is the aggregated interaction, adaptation and decision-making of individual agent at micro level that generates the ever-changing patterns of the whole system at macro level (Lambin and Geist, 2003).

Dynamics of urban landscape is triggered by intricate interactions of physical, socio-economic and anthropic factors (Batty, 2005; Yin and Muller, 2007). To be specific, human behavior and decisions play a predominant role in urban expansion (Andersson et al., 2002). These actions and interactions generally involve residential location decisions, urban developers' infrastructure construction, farmers' cultivation options, environmentalists' nature protection as well as policy makers' macro planning (Valbuena et al., 2010; Tian et al., 2011). ABM just provides a multi-agent system (MAS) context, in which human actors at different organization levels can interact both with each other and with a heterogeneous landscape (Ferber, 1999). MAS models focus on the diversity of agents, their behavior and interactions at a local level and thus is capable of representing the co-evolution of both human and their shared environment at an aggregate level (Verburg et al., 2005; Fontaine and Rounsevell, 2009), which make up the drawbacks that conventional simulation models of LUCC merely apply transition probabilities or differential equations at a single level (Verburg, 2006; Matthews et al., 2007).

A diverse range of applications of MAS models to urban phenomena have fully demonstrated this kind of modeling is well suited to synthetically express not only emerging landscape changes but micro behavior of both individuals and abstract entities (Verburg et al., 2005; Le et al., 2008). Despite its advantages, there have been many challenges facing MAS in modeling complex interactions between human diverse behavior and heterogeneous landscape in the coupled human-environment systems (Parker et al., 2003; Crooks et al., 2008). There are several challenges which are listed below that researchers have been devoted to cope with.

The first one is how to produce a heterogeneous landscape that truly reflects both biophysical and socioeconomic environment. Besides covering environment characteristics in various aspects, the landscape system is supposed to have a dynamically self-evolutionary mechanism beyond human control so that it can be co-evolving with the human system (Russell and Norvig, 1995; Le et al., 2008).

The second one is explicit clarification of the interactions between human actors and landscape, including specific decision-making processes and response mechanisms at different organization levels. The inherent complexity of interactions in the coupled human-environmental systems is so multifaceted that researchers have been searching for hybrid approaches to model urban dynamics (Le et al., 2008).

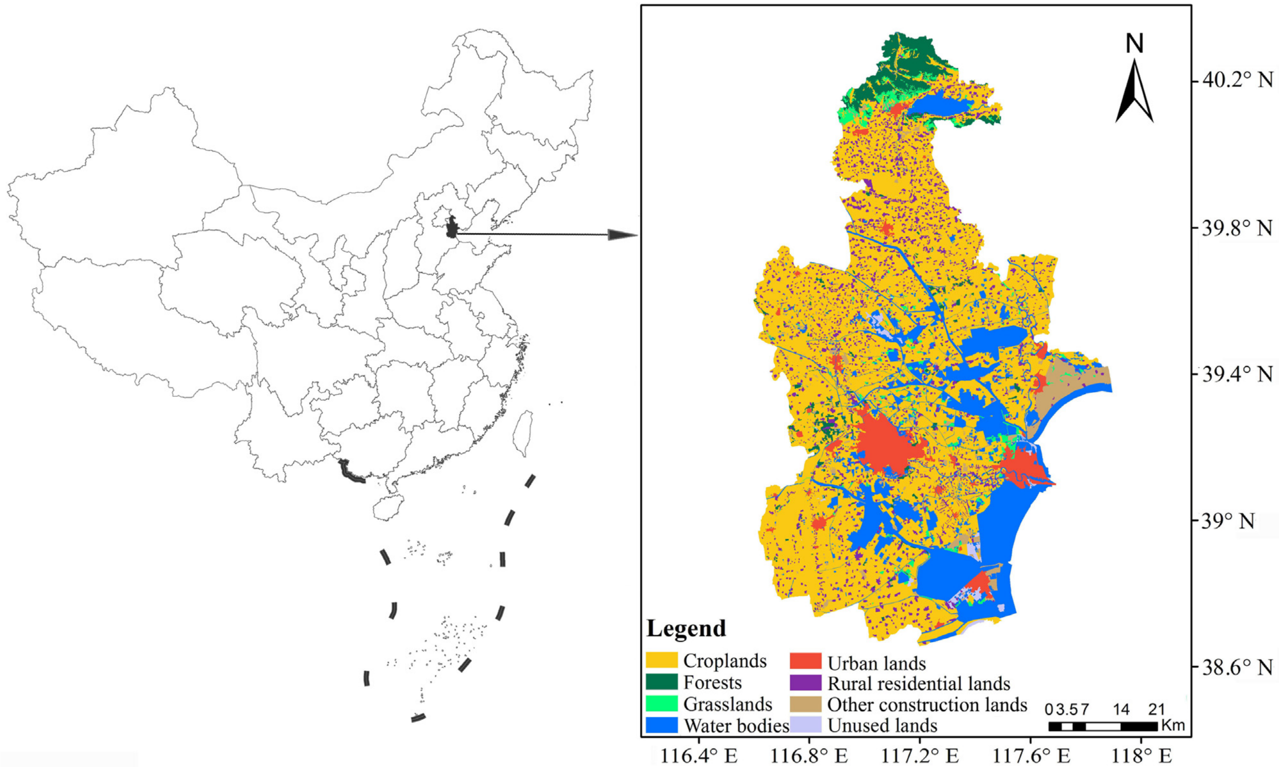

Fig. 1. Location and the land-use types of 2000 of the study area.