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Optimal rural land use allocation in central China: Linking the effect of spatiotemporal patterns and policy interventions

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A B S T R A C T

Rural land use development is experiencing a transition stage of socioeconomic and land use development in China. Historic land use transition process and policy interventions have key influence on the applicability of land use allocation solutions in future land use management. Strategic land use allocation is therefore required to possess a good adjustment capability to the transition process. Although heuristic optimization methods have been promising to solve land use allocation problems, most of them ignored the spatially explicit effect of historic land use transition and policies. To help resolve this issue, this study aims to optimize future land use pattern in the context of rural land use development. We took Yunmeng County, one of the typical major grain producing and rapidly urbanizing areas in central China, as a case study and solved the sustainable land use allocation problem by using an improved heuristic optimization model. The model was constructed based on the integration of a spatial discrete particle swarm optimization and cellular automata-Markov simulation approach. The spatiotemporal land use patterns and policy interventions were represented by the CA-Markov as in spatially explicit transition rules, and then incorporated into the discrete PSO for optimal land use solutions. We examined the influence of the joint effect of spatiotemporal land use patterns and policy interventions on the land use allocation outcome. Our results demonstrate the robustness and potential of the proposed model, and, more importantly, indicate the significance of incorporating the spatiotemporal land use patterns and policy interventions into rural land use allocation.

1. Introduction

Rural China is now at a transition stage of both socioeconomic and land use development (Wang, Liu, & Liu, 2013). At this stage, the core mission of the Chinese government is to narrow urban-rural gap and ensure land use sustainability (Liu et al., 2016). Rural areas in China, generally including counties, towns, and villages that are located outside cities, are of great importance to the transition process. However, various land use problems, represented by arable land loss, extensive agricultural activities and scattered distribution of settlements, emerge in the rural areas due to the Country's dual urban-rural economic structure. These problems may significantly hamper the rural development and intensify land use conflicts between economic development, agricultural protection, and ecosystem conservation together with the rapid urbanization and population growth (Liu, Fang, & Li, 2014). Scientific and efficient land use plans are thus urgently required to solve the land use problems and pursue sustainable development in rural China.

Rural land use planning, as a resource allocation problem, aims to seek feasible land use allocation solutions to balance land use requirements among stakeholders. It is a form of general planning policies in the land use management system of China (Wei, Wei, Cao, & Li, 2016), with the purpose of arranging land use quota/layout at a general scale of land use types, e.g., arable land, forest, and construction land (see Cao, Huang, Wang, & Lin, 2012; Ge, 2012; Liu, Yuan, He, & Liu, 2015). From the perspective of rural development, however, land use requirements will change with the rapid economic development and growing social needs (Chang & Ko, 2014; Li, Long, & Liu, 2015; Oliveira et al., 2007). These changes may render current allocation solutions inappropriate or

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even infeasible in future land use management. Strategic land use allocation is thus required to possess a good adjustment capability in response to change in land use demands (Diamond & Wright, 1989; Zhang et al., 2016). The insightful understanding of dynamic characteristics in rural land use system will provide solid support for the strategic allocation. In reality, the rural land use dynamics originate from two aspects: historic transition process and external interventions (e.g., policy) of land use systems. Historic land use transition process features a conditional link between past and present land use patterns, which is also known as temporal component (characteristic) of land systems. This link implies the driving forces of land use change, so it can provide the knowledge of transition inertia to future land use optimization (An et al., 2015; Rounsevell et al., 2012). The spatial allocation solutions without adequate exploration of this link may neglect the impacts of historic human decisions and feedback of socioeconomic process (Deng, Wang, Hong, & Qi, 2009; Matthews, Sibbald, & Craw, 1999). External intervention is another key factor to land use change. This impact is usually from new land use policies which are not implied in historic land use trends (Liu, Li, Shi, Zhang, & Chen, 2010). During the period of China's thirteenth five-year plan, the Chinese government has adopted a series of land use policies, e.g., “permanent farmland zoning around cites/towns” and “designation of ecological red lines” (Liu et al., 2014; Long, Li, Liu, Woods, & Zou, 2012). These policies may impose a remarkable impact on future land use. To date, how to coordinate land use plans with transition process of rural land use system and policy intervention is still a major challenge in the process of optimal land use allocation.

Land use allocation can be casted into a multi-objective combinatorial optimization problem (Tong & Murray, 2012). A variety of approaches have been developed to solve this complex optimization problem, including mathematical programming and heuristic optimization methods (Aerts, Eisinger, Heuvelink, & Steward, 2003; Mohammadi, Nastaran, & Sahebgharani, 2016; Zhou, 2015). Among these methods, mathematical programming, e.g., linear programming, interval programming, are time-related but spatially implicit, which cannot represent spatial land use pattern appropriately. Besides, these methods based on exact search may not reach the optima within a reasonable time when spatial objectives impose a large computational burden on the model (Aerts et al., 2003; Cromley & Hanink, 1999).

Heuristic optimization methods, by contrast, have the capability of addressing the shortcomings above in practice. Examples include simulated annealing, genetic algorithms, genetic programming, artificial immune system, ant colony optimization, and particle swarm optimization (Aerts & Heuvelink, 2002; Eldrandaly, 2010; Huang, Liu, Li, Liang, & He, 2013; Liu, Li, Shi, Huang, & Liu, 2012). These methods feature effectiveness for solving high dimensional problems and flexible frameworks for mapping problem solutions (Fogel, 2007; Xiao, 2008). This strength makes these heuristic methods potential to couple allocation optimization with land use dynamics process. In combination with geographical information systems (GIS), for example, heuristic methods can incorporate empirical knowledge on spatial patterns of land use system into the allocation per se and obtain spatially explicit optimal allocation solutions (Ligmann-Zielinska, Church, & Jankowski, 2008; Liu et al., 2015; Stewart & Janssen, 2014). These spatial patterns usually include land use suitability and spatial characteristics driven by interactions between individual decision makers and land parcels (e.g., contiguity, proximity, and compactness). Further, land use planners also attempted to constrain land use transition in allocation solutions with development cost and land use compatibility (Cao et al., 2012). The integration of spatial characteristics and land use conversion constraints can improve substantially the performance of heuristic models and generate the allocation solutions that are more reasonable. Moreover, heuristic methods also take quantity change in land demands as the temporal constraint for the allocation optimization based on the combination with system dynamics and Markov models (Liu, Ou, Li, & Ai, 2013; Sang, Zhang, Yang, Zhu, & Yun, 2011).

However, these heuristic allocation approaches still have drawbacks when dealing with dynamics in rural land use systems. The dynamic nature of land use system often requires that the allocation models not only consider the effects of present spatial patterns (e.g., spatial correlation and spatial suitability), but also incorporate (through, for example, simulation) the information of historic land use trends and policy interventions (An et al., 2015; Castella & Verburg, 2007; Huang, Pontius, Li, & Zhang, 2012). Existing heuristic optimization methods mainly focused on the effect of present spatial patterns and temporal constraint at the macro level of land use on the allocation outcome, while ignored the spatially explicit information of historic land use transition and policy impacts (Cromley & Hanink, 1999; Liu et al., 2015). Little is known in terms of how the joint effect of spatiotemporal land use patterns and policy interventions will influence the land use allocation outcome.

The objective of this study is thus to optimize future land use pattern in the context of rural land use development by taking into account the joint effect of spatiotemporal land use patterns and policy interventions. We took Yunmeng County, one of typical major grain producing and rapidly urbanizing areas in central China, as a case study and generated its sustainable land use plans by using an improved heuristic optimization model. The model was constructed based on the integration of a spatial discrete particle swarm optimization algorithm (sDPSO) and cellular automata (CA)-Markov analysis approach. The spatiotemporal land use patterns (i.e., suitability, conversion restraints, and historic transition probability) and policy interventions were simulated by the CA-Markov as in spatially explicit transition rules, and then incorporated into the discrete PSO. The relationships between spatiotemporal land use patterns, policy interventions and allocation optimization were further examined with a scenario analysis approach. By this way, we adjusted allocation optimization to the simulation of dynamic rural land use systems. The remainder of this article is organized as follows. Section 2 provides an introduction to the study area and data. Section 3 describes the land use allocation model sDPSO in detail and implements the model based on the data. Section 4 presents results and relevant discussion, and in the final section we conclude this study.

2. Study area and data

Our study area is Yunmeng County in Hubei province, China (see Fig. 1). In China, county is the third level in the administrative division hierarchy of province-prefecture/city-county-town-village. A county is usually regarded as a rural area, especially when it is located in agricultural zones. Yunmeng County is such an area in Hanjiang Plain at central China. It lies between longitude 113°37′E and 113°52′E and latitude 30°45′N and 31°12′N, and covers an area of approximately 60,530.94 ha (51.1 km × 24.45 km) with a population of 0.5779 million in 2013. A warm and humid continental monsoon climate dominates this study region, and makes it one of the top thirteen agricultural zones in China. Arable land is the major land use type of this area (occupying 69.26% in 2013), indicating the importance of this county for food security. However, land demands for urban settlement and subsistence agriculture increased dramatically with rapid economic development and population growth during the period of 2009–2013. This increasing land demand contributes to a series of land use conflicts, e.g., between