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Projections of future land use changes: Multiple scenarios-based impacts analysis on ecosystem services for Wuhan city, China

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ABSTRACT

Urbanization alters the supply of ecosystem services that are vital for human well-being. The loss of ecosystem services is particularly challenging in rapid urbanization areas where economic development needs to consume substantial natural resources. The quantitative and spatial optimization of land use provides an effective tool for rationally allocating land use structure and pattern to ensure the provision of expected ecosystem services. In this paper, we combine the Multi-Objective Programming and the Dyna-CLUE model to project land use changes in 2030 for Wuhan city under three scenarios, i.e., Business As Usual (BAU), Rapid Economic Development (RED), and Ecological Land Protection (ELP). The coupled model that integrates "top-down" and "bottom-up" processes is capable of obtaining the optimized land use patterns under different scenarios and examining the potential impacts of land use changes on ecosystem services in a spatially explicit way. We find that built-up land will continue its remarkable growth during 2015-2030 under the BAU scenario (grows by 96%) at the expense of ecological lands (decreases by 18%). Meanwhile, the predicted losses of ecological lands are 11% and 6% under the RED and ELP scenarios, respectively. Projected land use changes result in varying magnitudes of declines in ecosystem service values for BAU (11%), RED (6%) and ELP (2%) scenarios from 2015 to 2030. The ELP scenario, which incorporates ecological protection policies and spatial restrictions, plays a positive role in altering land use trends and mitigating ecosystem degradation. Finally, we establish an ecosystem service value change matrix to explain how interactions between land use types give rise to trade-offs among multiple ecosystem services. We find that conversions between ecological land use types can trigger trade-offs among ecosystem services, but the conversion from ecological lands towards urban land leads to a net loss of all individual ecosystem services. By linking land and ecological systems, the coupled modeling framework in this study can be useful for obtaining optimal ecosystem-based land use allocation strategies and provide scientific support for sustainable land use management.

1. Introduction

Humans consume a wide range of goods and services provided by ecosystems for survival and welfare (Costanza et al., 1997; Daily et al., 1997). Meanwhile, humans also modify ecosystems over time, intending to enhance the provision of certain types of ecosystem services (ES) to satisfy immediate human needs, such as food, fuel, and shelter (Foley et al., 2005), but often result in losses of other types of ES unintentionally (Defries et al., 2004). In the past few decades, driven by the growing needs arising from population growth, rapid urbanization and economic development, humans have changed ecosystems more drastically and extensively than ever before, e.g., over 60% of global ecosystems have been degraded (MEA, 2005), leading to substantial and largely irreversible loss of ES. Among all human activities, land use/land cover (LULC) change is most relevant to variations in the provision of multiple ES (Lawler et al., 2014), as certain ES are closely tied to specific types of LULC (Costanza et al., 1997; Rodríguez et al., 2006), e.g., timber and climate regulation are mostly provided by forests. Therefore, understanding the linkage between LULC and ES is of key interest to both researchers and policy-makers worldwide.

Studies have made advances in modeling LULC changes (e.g., Azadi et al., 2017), evaluating ES values (e.g., Costanza et al., 2014), and examining responses of ES to LULC dynamics (e.g., Newbold et al., 2015). These studies highlight the profound influences of LULC changes on the provision of ES. For example, the conversion from ecological lands towards urban land can disrupt surface water balance, increase

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greenhouse gas emissions, and influence regional climate (Foley et al., 2005). The impacts of LULC changes on ES vary widely across different biophysical or socioeconomic settings (Defries et al., 2004), and across different spatial or temporal scales (Clough et al., 2016). Recent research demonstrates that multiple services provided by ecosystems are not independent of each other (Rodríguez et al., 2006). Hence, LULC changes aiming to maximize one particular type of ES may lead to losses of other types of ES, suggesting the existence of trade-offs in the provision of ES (Haase et al., 2012; Rodríguez et al., 2006). Though invisible, trade-offs among multiple ES are taking place all the time, which are often poorly taken into account and thus may cause unintended environmental consequences. Therefore, empirical knowledge of how interactions between LULC types bring about trade-offs among multiple ES is needed for sustainable management of ecosystems.

The relationship between ES and LULC highlights the role of ES in guiding land use planning and decision-making to develop sound management strategies (DeFries et al., 2004). Specifically, ES can be integrated into land use planning in two ways, i.e., serving as an objective of land use optimization models to propose ecologically-friendly land use schemes, or being used for evaluating, comparing, and selecting land use schemes under multiple planning scenarios. For example, Chuai et al. (2013) developed a land use optimization model with the goal of increasing terrestrial ecosystem carbon storage. The model obtained a land use scheme that can bring about a 2% relative increase in carbon storage from 2005 to 2020. Birch et al. (2010) designed three ecosystem restoration scenarios with different discount rates and performed a cost–benefit analysis to identify the best scheme that produces the highest increase in ES with the lowest cost. In this study, ES are used in both ways to inform land use planning, including the design of an "Ecological Land Protection" scenario, and the evaluation of ecosystem responses to land use changes.

Land use optimization models involve complicated processes with competing objectives (Liu et al., 2015a). Existing approaches that simulate these processes can be divided into two categories: bottom-up and top-down. The Multi-Objective Programming (MOP), a top-down approach, is useful for solving problems with conflicting objectives in complex land systems, particularly when incorporating macroeconomic policies (Sadeghi et al., 2009). However, the MOP cannot handle spatial optimization. The Cellular Automata, which is a bottom-up approach, is capable of generating optimized land use spatial patterns (Wang et al., 2015), but it often relies on other models to design conversion rules. The Ant Colony Optimization is a bottom-up approach that solves optimization problems through feedbacks among "ants" (Liu et al., 2008), but it fails to capture the spatial dynamic and heterogeneity of the environment. Most of these optimization models focus on only one aspect, either quantitative optimization of land use structures or spatial optimization of land use patterns, which have limitations. For example, it may not be possible to allocate the optimized land use structure to a specific location due to spatial restrictions, and the aggregated land area from allocated spatial patterns may fail to meet the requirements of different economic sectors. Therefore, it is necessary to adopt a coupled model to optimize both land use quantitative structure and spatial pattern from the top-down and bottom-up perspectives, simultaneously.

In this paper, we propose a coupled model based on the MOP algorithm and the Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) model to simulate land use changes under three scenarios, i.e., Business As Usual (BAU), Rapid Economic Development (RED), and Ecological Land Protection (ELP). The MOP algorithm seeks optimized solutions for each land use type subject to a series of constraints specified by a given scenario. The Dyna-CLUE model, which is dynamic and spatially explicit, allocates the predicted land use changes to grid cells following a bottom-up process (Verburg and Overmars, 2009). The process determines the most suitable land use for each grid cell based on location contexts, the total area of each land use type (derived from the MOP), and a set of rules of spatial restriction (e.g., nature reserves) (Verburg et al., 2012). The combination of the MOP and the Dyna-CLUE makes it possible to optimize the land use quantitative structure and allocate corresponding land use changes to the most suitable location.

Measuring the economic value of ES provides a basis for the inclusion of ES in land use planning and the quantification of ecosystem responses to land use changes. Methods of ES valuation can be divided into two primary types. The first type involves data-based approaches, which combine ecological models and primary data to quantify ecosystem processes and functions that underlie ES, and then convert the derived ES into market prices (Martínez-Harms and Balvanera, 2012). The data-based approaches are data-demanding and complex, and thus are often applied in small-scale studies that focus on a few types of ES. The second type includes the proxy-based approaches, which rely on "benefits transfer" with secondary data such as LULC information (Eigenbrod et al., 2010; Plummer, 2009). For example, the estimated value for each land use type can be transferred from one location to another with similar conditions (Costanza et al., 1997). Although lacking consideration of ES variations over space and time (Eigenbrod et al., 2010; Plummer, 2009; Song et al., 2015), the proxy-based methods are more commonly used due to simplicity and the widespread availability of LULC data. This study adopts the proxy-based approach for the valuation of ES, because it is effective to model the trade-offs among multiple ES arise from land use changes. Moreover, it facilitates the spatial representation of ES, including the spatial distribution of each individual type of ES, and key areas that undergo trade-offs among ES (Martínez-Harms et al., 2016). Finally, this approach is also useful to compare the costs and benefits of ecosystem-based management among different scenarios, which can be difficult for the data-based approach when future data are unavailable.

In this paper, we present a case study in a megalopolis in China to investigate how land use changes under different scenarios will affect the provision of ES by combing a coupled land use optimization model and a proxy-based ES valuation model. Specific objectives include (1) exploring the spatial determinants of the occurrence of each land use type based on a spatial logistic regression model; (2) predicting the spatial-temporal dynamics of land use in 2030 using the coupled MOP and Dyna-CLUE model under three different scenarios, i.e., BAU, RED, and ELP; (3) assessing the effects of land use dynamics on total ES values and trade-offs among multiple ES under the three scenarios.

2. Study area

Wuhan city, the capital of Hubei Province, is located in the middle reaches of the Yangtze River. The city is comprised of thirteen administrative districts (seven urban districts and six rural districts), covering an area of ~8450 km^2 between latitudes of 29°58′–31°22′ N and longitudes of 113°41′–115°05′ E (Fig.1). Wuhan city experiences a subtropical humid monsoon climate, with a mean annual temperature of 15.8–17.5 °C and a mean annual precipitation of 1150–1450 mm. Flat plains (< 100 m) dominate the terrain of Wuhan, while mountains (> 500 m) are mainly located in the northwestern and northeastern parts of the city. We can observe a few low hills in central and southern parts of the city. The forests are mainly distributed in these hilly areas. In addition, surface water accounts for a substantial area of Wuhan (approximately 26%), primarily concentrated in the central part of the city, forming large urban lakes such as East Lake, South Lake and Sha Lake.

Wuhan city is a megalopolis in Central China with a total population of 10.61 million. The Gross Domestic Product (GDP) reached 1,100 billion Chinese Yuan (CNY) in 2015, which ranked eighth among all the cities in China. During 2000 to 2015, Wuhan city has been experiencing accelerated urbanization, leading to extensive expansion of built-up land (from 65,864 ha to 136,277 ha) encroaching the surrounding ecological lands (i.e., cropland, woodland, grassland and water areas). From 2000 to 2015, the total area of ecological lands in Wuhan has decreased by 8%, and the areas of cropland, woodland, grassland