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Urban expansion simulation and the spatio-temporal changes of ecosystem services, a case study in Atlanta Metropolitan area, USA

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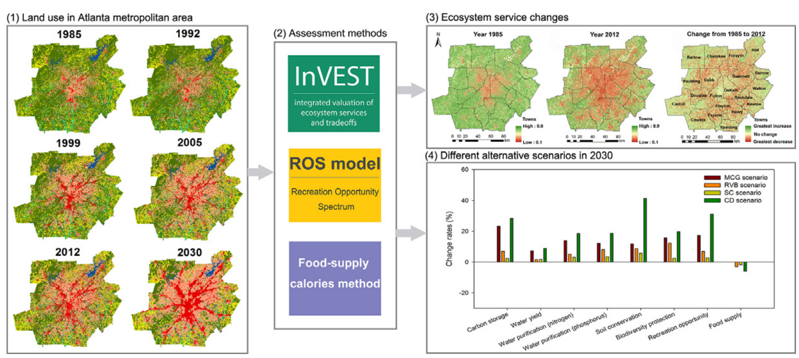
HIGHLIGHTS

- A framework for assessing the comprehensive ecosystem service was established.
- Future land use has been simulated by using the Markov-logistic-CA model.
- Six influential factors which affected the ecosystem services (ESs) were selected.
- Four alternative scenarios have been developed to enhance the ESs.
- The improvement for the supply of ESs should be integrated into land use planning and decision making.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban expansion can lead to land use changes and, hence, threatens the ecosystems. Understanding the effects of urbanization on ecosystem services (ESs) can provide scientific guidance for land use planning and the protection of ESs. We established a framework to assess the spatial distributions of ESs based on land use changes in the Atlanta Metropolitan area (AMA) from 1985 to 2012. A new comprehensive ecosystem service (CES) index was developed to reflect the comprehensive level of ESs. Associated with the influential factors, we simulated the business as usual scenario in 2030. Four alternative scenarios, including more compact growth (MCG), riparian vegetation buffer (RVB), soil conservation (SC), and combined development (CD) scenarios were developed to explore the optimal land use strategies which can enhance the ESs. The results showed that forest and wetland had the greatest decreases, while low and high intensity built-up lands had the greatest increases. The values of CES and most of ESs decreased significantly due to the sprawling expansion of built-up land. The scenario analysis revealed that the CD scenario performs best in CES value, while it performs the worst in food supply. Compared with the RVB and SC scenarios, MCG scenario is a more optimal land use strategy to enhance the ESs without at the expense of food supply. To integrate multiple ESs into land use planning and decision making, corresponding land management policies and ecological engineering measures should be implemented to enhance: (1) the water yield and water purification in urban core counties, (2) the carbon storage, habitat quality, and

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recreational opportunity in counties around the core area, and (3) the soil conservation and food supply in surrounding suburban counties. The land use strategies and ecological engineering measures in this study can provide references for enhancing the ESs in the AMA and other metropolitan areas.

1. Introduction

Since the mid-20th century, many American metropolises have experienced dramatic growth, dominated by expanding urbanization, spreading outward from the urban core towards the suburbs (BenDor et al., 2017). Urban expansion rates have exceeded population growth rates; under current trends, a tripling of urban area is projected to occur by 2030 (Seto et al., 2012). While urban development has always been viewed as a sign of regional economic prosperity, human land use and transformation has led to a series of environmental issues. Deforestation in the process of urbanization would increase the soil erosion and affect climate regulation (Pullanikkatil et al., 2016). Built-up land expansion and the fragmented landscape also can lead to lower food supply, carbon sequestration, soil water storage, biodiversity and so on (Li et al., 2016a; Li et al., 2017). The ecosystem service (ES) concept, which is defined as the beneficial functions supplied to human society by ecosystems, has been increasingly applied to assess the probable impacts of environmental change on human wellbeing (Costanza et al., 2017).

In recent years, there is growing awareness that land use change is one of the fundamental factors for influencing the ESs (Deng et al., 2016). The mechanisms of how land use changes affect ESs has become a hot issue (Sutherland et al., 2014). A lot of researchers tried to explore how land use changes affect the process of ESs (Abram et al., 2014; Li et al., 2016a; Wang et al., 2017a). Most of studies focused on exploring the dynamics of ESs and their variations in relation with land use changes in natural and semi-natural landscapes (Frank et al., 2017; Pullanikkatil et al., 2016; Tian et al., 2016; Tolessa et al., 2017); however, few studies have evaluated the temporal and spatial dynamics of multiple ESs in urban ecosystems or predicted future changes of ESs according to land use simulations. There is growing awareness that the practices and policies of urban land use management can help manage urbanization and increase the supply of ESs; however, providing recommendations to policy makers about how to integrate the ES framework into decision making remains challenging (Albert et al., 2016). Assessing future ESs that is based on land use simulations can help protect urban ecosystems and promote sustainable development (Yao et al., 2015). Currently, different types of models such as the Markov Chain (MC) model, regression model, and Cellular Automata (CA) model are widely used in land use simulations (Guan et al., 2011). Among them, Markov Chain (MC) model and regression model are empirical and statistical models, while CA model is the dynamic model. Dynamic model is more appropriate for predicting future land use changes and superior to other models in terms of expressing spatial information (Hayek et al., 2016). However, the empirical and statistical models can complement dynamic simulations (Han and Jia, 2017). Thus, a combination of a CA model, logistic regression, and an MC model has been adopted for urban expansion modeling studies (Arsanjani et al., 2013).

Scenario analysis through establishing alternative plans and policies is an effective approach for assessing the ESs based on land use changes (Burkhard et al., 2012; Martinez-Harms et al., 2017). Simulating land use allows more accurately forecasting and analyzing the outcomes of implemented plans and policies (Deng et al., 2016). Most scenario analysis studies predict future urban development and changes of ESs based on local land use policies (Baral et al., 2014; Gascoigne et al., 2011; Lautenbach et al., 2017), but few studies have designed alternative scenarios to address problems with current regional urban planning and ES protection. Simulating land use scenarios that aim to improve one specific ES or multiple ESs can not only validate the potential effectiveness of alternative scenarios but also provide feasible land use planning advice for local governments. There are now many ES models available, and most of them either incorporate or suggest analysis of future scenarios that represent storylines of various land use and natural resource management decisions (Berg et al., 2016). Integrating the ES models into alternative scenarios design has become an effective approach for analyzing the trade-offs of ESs and exploring optimal land use strategies (Goldstein et al., 2012; Martinez-Harms et al., 2017; Zheng et al., 2016).

Metropolitan areas are consisted of densely populated and highly urbanized areas and less-populated surrounding territories (Cidell, 2010). During recent decades, these areas have experienced rapid urban growth, accompanied by substantial landscape changes and associated ESs degradation (Bhatti et al., 2015; Peng et al., 2017). Simulating urban expansion and assessing the ESs in metropolitan areas is highly significant for urban land planning and ES protection in the USA. The Atlanta metropolitan area (AMA) is one of the fastest-growing large metropolises in the USA (Liu and Yang, 2015). This study mainly developed a new comprehensive ecosystem service (CES) index and assessed the spatial and temporal changes of multiple ESs in the AMA. The ESs include carbon storage, water yield, water purification, soil conservation, biodiversity protection, recreational opportunity, and food supply. We mainly aims to: (1) assess the CES values by integrating different models; (2) develop different alternative scenarios to explore the optimal land use strategies which can increase the supply of ESs; (3) put forward corresponding land management policies and ecological engineering measures to enhance the ESs for different regions in the AMA.

2. Material and methods

2.1. Study area

The AMA (83°27′–85°21′W, 33°11′–34°31′N) is located in the low foothills of the southern Appalachian Mountains in northern Georgia, USA. The 20 counties in this study (Fig. 1) reflect those included in the AMA definition from 1999 (USCB (United States Census Bureau), 1999). Its total area is approximately 16,605 km^2. The average elevation is approximately 300 m above sea level. The northern and some western counties tend to have higher elevations and are significantly hillier than the southeastern counties. The AMA is characterized by a humid subtropical climate with four seasons. It has a mean annual temperature of 17 °C and an average precipitation of 1258 mm (NCEI (National Centers for Environmental Information), 1985). From 1985 to 2012, the total population in the AMA increased from 2.6 million to 5.4 million. Fulton, Dekalb, Clayton, Cobb and Gwinnett counties were identified as the urban core (O'Lenick et al., 2017). According to the United States Census Bureau, the population of each of these five counties was >260,000 in 2012. Meanwhile, their population densities exceeded 700 people per square kilometer, which were higher than 97% of counties in the USA. In addition, the AMA is the "economic engine" of the southeastern USA (Clark, 2014). The Gross Domestic Product of the AMA ranked No. 10 out of 382 USA metropolitan areas (BEA (Bureau of Economic Analysis), 1985).

2.2. Data sources and ES typology

The Millennium Ecosystem Assessment (MEA) has stimulated the studies of ESs around the world (Costanza et al., 2017; Millennium Ecosystem Assessment (MEA), 2005; Wolff et al., 2015). ESs were