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Assessing the potential impacts of urban expansion on regional carbon storage by linking the LUSD-urban and InVEST models

Chunyang He [a, 1], Da Zhang [a, b, 1], Qingxu Huang [a, *, 1], Yuanyuan Zhao [c, 1]

[a] Center for Human-Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Beijing Normal University, Beijing 100875, China

[b] College of Resources Science & Technology, Beijing Normal University, 19 Xinjiekouwai Street, Beijing 100875, China

[c] Key Laboratory of Soil and Water Conservation and Desertification Combating, Ministry of Education, School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

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The timely and effective assessment of the impacts of urban expansion on regional carbon storage is an important issue in the fields of urban ecology and sustainability science. This study used a new model to assess the impacts of urban expansion on regional carbon storage by linking the LUSD-urban and InVEST models. First, the LUSD-urban model was used to simulate urban expansion. Then, the InVEST model was adopted to assess the impacts on regional carbon storage. The linked model combines the strengths of these two models. Not only can it simulate and project the process of urban expansion but it can also assess the impacts of urban expansion on regional carbon storage. A case study in Beijing showed that the relative error between the simulated carbon storage loss and the actual loss was less than 12%. We argue that the linked model can be applied to assess the ecological effects of future urban expansion.

1. Introduction

Regional carbon storage is the cumulative amount of carbon stored in a regional terrestrial ecosystem. It is composed of four elements: aboveground carbon storage (AGC), belowground carbon storage (BGC), soil organic carbon storage (SOC), and dead organic matter carbon storage (DOC) (IPCC, 2006; Tallis et al., 2013; Turner et al., 1995). Regional carbon storage is a widely recognized indicator of ecosystem services because it is closely related to the productivity and climate regulation capacity of terrestrial ecosystems. Urban expansion is a land-use change process that transforms non-urban land to urban land (Bai et al., 2012; López et al., 2001). It has had significant impacts on regional carbon storage and the carbon balance due to the increase in impervious surfaces and loss of natural vegetation, which in turn has seriously threatened the provision of regional ecosystem services and ecological resilience (Eigenbrod et al., 2011; Hutyra et al., 2011; Imhoff et al., 2004; Lawler et al., 2014; Svirejeva-Hopkins and Schellnhuber, 2008). At present, the world is experiencing remarkable urban expansion and this trend is likely to continue in the future (Grimm et al., 2008; Wu, 2010). The global urban land area is projected to triple by 2030, from circa 0.65 million km^2 in 2000 to 1.86 million km^2 in 2030 (Seto et al., 2012). Therefore, timely and effective assessments of the impacts of urban expansion on provision of regional ecosystem services (e.g., carbon storage) are important for climate change mitigation/adaptation and maintaining regional sustainable development (Eigenbrod et al., 2011; Pataki et al., 2006), and has become an important issue in the fields of urban ecology and sustainability science.

The present methods used to assess the impacts of urban expansion on regional carbon storage mainly include field surveys (Golubiewski, 2006; Hutyra et al., 2011; Ren et al., 2011), remote sensing (Buyantuyev and Wu, 2009; Fu et al., 2013; Imhoff et al., 2004; Lu et al., 2010), and model simulations (Gao et al., 2005; Nelson et al., 2010; Pei et al., 2013; Sohl et al., 2012; Zhang et al., 2012, 2008; Zhao et al., 2013). Among these methods, models are becoming increasingly important because they can simulate, predict, and assess the impacts of urban expansion on regional carbon storage at different scales (Sohl et al., 2012; Yu et al., 2009; Zhang et al., 2012, 2008). For example, Zhang et al. (2012) used a process-based Dynamic Land Ecosystem Model (DLEM) to simulate

* Corresponding author.
E-mail address: qxhuang@bnu.edu.cn (Q. Huang).

[1] These authors contributed equally to this work.

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vegetation carbon storage and SOC in the Southern United States, and assessed the carbon dynamics of urbanized lands during the period of 1945–2007. Gao et al. (2005) adopted the Carbon Exchange in the Vegetation-Soil-Atmosphere System (CESVA) model to assess the impacts of urban expansion on SOC in the cropping–grazing transition zone of China during 1981–2000. Yu et al. (2009) used the Carnegie Ames Stanford Application (CASA) productivity model to obtain net primary productivity for Shenzhen, China, and further estimated the effect of urban expansion on vegetation carbon storage from 1990 to 2005. However, few models can assess the potential impacts on regional carbon storage due to future urban expansion (Pei et al., 2013). The reasons for this deficiency are mainly: (1) existing urban expansion models do not have adequate capability to accurately predict future urban expansion because the process of urban expansion is complex and involves various geophysical and socioeconomic drivers; and (2) many ecological models cannot easily and flexibly assess the impacts of urban expansion on regional carbon storage because a large number of parameters and complex operational processes are required to drive these models.

Regional urban expansion models based on cellular automata (CA) have proliferated because CA models can simulate the spatial and temporal change of urban area in a simple and flexible way. CA was originally propose by J. von Neumann in the late 1940s and applied by Tobler (1979) to simulate geographic phenomena. Since the appearance in the early 1990s (Batty and Xie, 1994; White and Engelen, 1993), considerable advances in developing and improving the CA-based urban expansion models have been achieved (Itami, 1994; Santé et al., 2010). Recently, new techniques, such as ant colony optimization (Liu et al., 2008a), kernel-based learning method (Liu et al., 2008b), and integration of landscape metrics (Liu et al., 2014), have been successfully employed to improve the performance of the model.

The Land Use Scenario Dynamics-urban (LUSD-urban) model was developed as a regional urban expansion scenario model by integrating CA and system dynamics (SD) models. It can simulate both macro- and micro-sale drivers of land-use and land-cover change (LUCC) in a spatially explicit way, and therefore effectively simulate the spatial process of urban expansion (He et al., 2006, 2005). Building upon previous LUSD models (He et al., 2008, 2006, 2005), a new LUSD-urban model incorporated a potential model, which represented the spatial interactions of capital and population, and their impacts on urban expansion, with the original LUSD model. The new model significantly enhanced the capability and accuracy of simulated results. More recently, He et al. (2013b) have successfully combined a gravitational field model, which simulates the influence of urban flows (e.g., flows of people, material and information), with the LUSD-urban model to simulate urban expansion in a megalopolitan cluster area and produced more accurate simulation results than the CA model that did not account for urban flows.

Two primary methods have been applied to estimate carbon storage, the carbon density method and the biogeochemical model. The former method used global or regional carbon density profiles of different vegetation and soil types to estimate carbon storage. This method is relatively easy but ignore species composition, age structure, and other regional characteristics that can affect carbon storage calculation (Huang et al., 2014a; Nelson et al., 2009). The latter method simulated carbon storage by process-based ecological models, for instance, the Biome-BGC model (Robinson et al., 2013) and the Century model (Schaldach et al., 2011). Although these process-based models might provide more accurate estimation of carbon storage than the carbon density method, they demanded a large amount of input data and computational efforts (Filatova et al., 2013). Published estimation of carbon storage between the two methods may vary significantly because of the availability and comparability of input data, suitability of method in a specific region, as well as uncertainties of data and method (Ni, 2013).

Previous studies have showed that the InVEST (Integrated Valuation of Environmental Services and Tradeoffs) model can estimate the carbon storage in an easy and reliable way (Leh et al., 2013; Nelson et al., 2010; Polasky et al., 2011). The InVEST model is an ecosystem service assessment model, which was developed by the Natural Capital Project (www.naturalcapitalproject.org), supported by Stanford University, the University of Minnesota, The Nature Conservancy, and the World Wildlife Fund (Tallis et al., 2013). Based upon the carbon density method, it uses maps of land-use and land-cover types and data on carbon stock in four carbon pools (i.e., aboveground biomass, belowground biomass, soil, and dead organic matter) to estimate the influence of LUCC on the amount of carbon sequestration over time (Tallis et al., 2013). Recently, many researchers have used the InVEST model to conduct empirical studies at different scales. For example, Nelson et al. (2010) simulated changes in global urban land and cropland from 2000 to 2015, and assessed the impacts of these changes on regional carbon storage in different countries and regions based on the InVEST model. At the national scale, Leh et al. (2013) used the InVEST model to analyze the impacts of land-use change on regional carbon storage for Ghana and Cote d'Ivoire from 2000 to 2009. Polasky et al. (2011) evaluated the impacts of actual land-use change, as well as a suite of alternative land-use change scenarios on carbon storage in Minnesota, USA, from 1992 to 2001, and further discussed how to improve regional carbon storage through land management policies. Delphin et al. (2013) developed a decision tree-based framework to determine potential damage to subtropical forests from hurricanes in the Lower Suwannee River and Pensacola Bay watersheds in Florida, USA, and estimated the potential loss of AGC due to forest change.

As the political, economic, and cultural center of China, Beijing has experienced rapid economic growth and urban expansion since the Chinese government adopted the *Reform and Opening-up* policy in 1978 (He et al., 2013a; Wu et al., 2006). From 1978 to 2012, its gross domestic product (GDP) grew from 10.88 billion to 1787.94 billion RMB yuan; while its urban population grew from 4.79 million to 17.84 million. The percentage of the total population living in urban areas (i.e., urban population) increased from 54.96 to 86.20% (Beijing Municipal Statistical Bureau, 2012). Existing studies have suggested that urban expansion in Beijing has resulted in a large regional carbon storage loss in recent years. Over the period of 1988–2000, urban expansion in Beijing encroached on circa 900 km^2 of cropland, and consequently resulted in a vegetation carbon storage loss of 0.82 Gg ($1G = 10^9$) (Jiang et al., 2008). However, few studies have assessed the potential impacts of future urban expansion on regional carbon storage in Beijing.

To effectively assess the potential impacts on regional carbon storage due to future urban expansion, we developed a new model by linking the LUSD-urban and InVEST models. First, future urban expansion was simulated using the LUSD-urban model. Then, the InVEST model was used to assess the potential impacts of future urban expansion on regional carbon storage. The linked model combines the strengths of both the LUSD-urban and the InVEST model; i.e., the accurate simulation of regional urban expansion and the quantitative estimation of carbon storage respectively, to effectively assess the potential impacts of future urban expansion on regional carbon storage. We validated our linked model by comparing simulated results with historical records in a case study of the Beijing metropolitan area of China from 1990 to 2011. Finally, we used the linked model to assess the potential impacts of future urban expansion on regional carbon storage in the same area from 2011 to 2030.