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A land-cover-based approach to assessing ecosystem services supply and demand dynamics in the rapidly urbanizing Yangtze River Delta region

Yu Tao[a,b], Hongning Wang[a], Weixin Ou[a,b,*], Jie Guo[a,b]

[a] College of Land Management, Nanjing Agricultural University, Nanjing, 210095, China
[b] National & Local Joint Engineering, Research Center for Rural Land Resources Use and Consolidation, Nanjing, 210095, China

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ABSTRACT

It is essential to appraise the impacts of land use and cover change on both the supply and demand sides of ecosystem services to formulate effective land use policies towards sustainable development. However, it remains challenging to accurately quantify ecosystem services supply and demand with comparable measurement units. Burkhard et al. (2012) proposed the use of an expert-based matrix model to assess ecosystem services supply and demand per land cover class in comparable semi-quantitative units. In this study, we improved the matrix model by measuring the levels of uncertainty that arise from expert estimation to obtain more accurate estimates, and by proposing a more adequate synthesis method to create the comprehensive index for quantifying ecosystem services supply–demand budgets with semi-quantitative estimates in the matrices. Taking the rapidly urbanizing Yangtze River Delta (YRD) region of China as an example, we used the improved matrix model to characterize relative changes in ecosystem services supply and demand in response to land use and cover change during 1985–2015. According to our land-cover-based matrix model, the two dominant land cover types (built-up area and rice fields) in the four largest cities (Shanghai, Nanjing, Hangzhou, and Suzhou) of the YRD region all exhibited greater demand for freshwater, flood protection, water purification, and erosion regulation than the provision of these hydrological services. Consequently, the four cities also exhibited greater demand for these four hydrological services than the supply of these services from local ecosystems. During the past three decades, the built-up area of the four largest cities expanded by 2.2–4.9% annually, along with an annual decrease rate of 1.9–4.6% for croplands (including rice fields and rainfed croplands). The rapid urban expansion and the huge loss of croplands caused the supply–demand budget index value of food production service to decrease by 1.7–3.7% annually, indicating large decreases in the provision of food production service, alongside large increases in food demand. Among the three categories of ecosystem services, the regulating services were in severe short supply for the four largest cities of the YRD region, while the cultural services were in sufficient supply during the past three decades. In contrast, the provisioning services shifted from sufficient supply in 1985 to insufficient status in 2015, primarily due to the rapid urban expansion. Our results illustrate clear and direct impacts of urban encroachment on both the supply and demand sides of multiple ecosystem services. This improved matrix model can be applied to assess ecosystem services supply and demand dynamics for other rapidly urbanizing regions.

1. Introduction

The provision of ecosystem services, defined as the benefits that ecosystems generate and deliver to humans (Daily et al., 2000), has become one of the critical concepts and indicators for measuring ecosystem health and sustainability since the Millennium Ecosystem Assessment., (2005) and the pioneering work on the classification and valuation of ecosystem services by Costanza et al. (1997); Daily et al. (2000); and de Groot et al., (2002). To date, a large quantity of literature has evaluated the provision of ecosystem services in different regions of the world using the market-valuing method (Peng et al., 2015; Xie et al., 2015). Spatially explicit modeling tools, such as the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) models developed by the Natural Capital Project, have also been widely used to map the provision of ecosystem services and their spatial interactions (i.e., synergies and tradeoffs) across heterogeneous landscapes (Nelson et al., 2009; Qiu and Turner, 2013; Peng et al., 2017; Zhang et al., 2017a; Xie et al., 2018). Nevertheless, the underlying

* Corresponding author at: College of Land Management, Nanjing Agricultural University, Nanjing 210095, China.
E-mail address: owx@njau.edu.cn (W. Ou).

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causes of ecosystem degradation (e.g., water quality degradation) are the imbalance between ecosystem services supply and demand, including declines in ecosystem services supply (e.g., decreased capacity of nutrient retention from natural areas) and growing demands for ecosystem services (e.g., increased nutrient load from agricultural areas). To formulate sustainable ecosystem management options, government agencies require information from both the supply and demand sides of ecosystem services.

In contrast to ecosystem services supply, research on ecosystem services demand has not received much attention until recent years. The definitions of demand for ecosystem services vary among different categories of ecosystem services. Demand for provisioning services is defined as the amount of ecosystem goods (e.g., freshwater, food, and biomass energy) required or desired per unit space and time (Burkhard et al., 2012; 2013). Demand for regulating services was defined by Villamagna et al., (2013) as the amount of regulation (e.g., air quality regulation) needed to maintain desirable environmental conditions (e.g., air quality standards). Demand for cultural services is defined as the expression of individual agent's preferences (e.g., visits to parks) for specific attributes of the service (Schröter et al., 2012). Based on these definitions, researchers have explored various methods to assess demand for ecosystem services (Wolff et al., 2015). Demand for provisioning services has been quantified based on direct use and consumption (Kroll et al., 2012; Boithias et al., 2014), whereas demand for regulating services has been quantified using risk exposure and vulnerability assessments (Stürck et al., 2014; 2015). Demand for cultural services is commonly expressed as the preferences and values related to the service (Baró et al., 2016; Vigl et al., 2017). Although much progress has been made, several obstacles remain in assessing demand for ecosystem services. Currently, the assessments of demand for regulating and cultural services still lack clear concepts and methodologies to obtain reliable results. In most cases, the supply and demand sides of regulating and cultural services are estimated with different measurement units, making it difficult to synthesize and compare the results from both sides.

In fact, changes in land use and land cover have clear and direct impacts on both the supply and demand sides of ecosystem services. Based on this assumption, Burkhard et al. (2012) proposed the land-cover-based matrix model to assess ecosystem services supply and demand per land cover class through expert estimation. In the matrix model, the supply and demand matrices are created by relating different land cover classes (in rows) with multiple ecosystem services (in columns). Estimates in the supply/demand matrix are put into comparable semi-quantitative units in the range between 0 and 5, where 0 indicates no relevant supply/demand and 5 indicates the highest relevant supply/demand (Jacobs et al., 2015). The supply–demand budget matrix is further created by combining the two matrices, with estimates ranging between −5 (demand vastly exceeds supply) and 5 (supply vastly exceeds demand). The matrix model facilitates rapid assessment of ecosystem services supply and demand, and generates results with strong implications for land use policy-making in different regions, while requiring only the land cover data and local expert knowledge. Because of these advantages, Burkhard's research on the matrix model has been well acknowledged since its publication in 2012. The matrix model has so far been applied to assess ecosystem services supply and demand in many European and Asian regions (Nedkov and Burkhard, 2012; Stoll et al., 2015; Cai et al., 2017).

However, current applications of the matrix model still need further improvements in the following two aspects. Firstly, expert-based assessment of ecosystem services supply and demand can bring about high uncertainty (even bias and errors) in the estimates (Hou et al., 2013). For instance, Li et al. (2016) and Zhang et al., (2017b) independently assessed ecosystem services supply and demand in the same region using the matrix model, yet they obtained quite different estimates with distinct groups of experts. Despite differences between the studies, most current studies did not measure the levels of uncertainty in the estimates to address the scoring variability issue (Stoll et al., 2015; Campagne et al., 2017). Secondly, semi-quantitative estimates in the matrices restrict comparison and analysis across ecosystem services and land cover classes. For instance, as Schröter et al. (2012) noted, the land cover class "broad-leaved forest" is, in principle, unable to supply global climate regulation (score 5) at comparable levels to demand on the land cover class "industrial or commercial units" (also scored with 5 in Burkhard's research). This disadvantage makes it inappropriate to use the additive method to create the comprehensive index for quantifying supply–demand budgets. Methods that can more adequately cope with semi-quantitative data need to be explored to synthesize the results.

Based on the above assessment, we asked the following key research questions in this study: (1) How can we improve the matrix model to better measure ecosystem services supply–demand budgets? (2) How have ecosystem services supply and demand changed over time in response to land use and cover change in rapidly urbanizing regions? (3) What are relevant policy implications for land use regulation in the region? To answer these three questions, we aim to use and improve the matrix model to characterize relative changes in ecosystem services supply and demand caused by land use and cover change in the rapidly urbanizing Yangtze River Delta region of China over the past three decades, and formulate relevant land use policies accordingly.

2. Materials and methods

2.1. Study area

The Yangtze River Delta (YRD) region is located in the eastern part of China. It includes 16 major cities, and has grown into one of the most densely populated (at an annual population growth rate of 3.0%), rapidly urbanized (at an annual urban land growth rate of 9.2%), and economically developed (at an annual GDP growth rate of 15.7%) regions in China over the past three decades (Cai et al., 2017). By 2014, the region supported 8.1% of the nation's population and contributed 15.9% of the national total GDP, despite representing only 1.2% of the total land area of China (Xu et al., 2016). The rapid urbanization in the YRD region has dramatically changed land use and land cover patterns, causing degradation of ecosystem services capacity, such as water purification, flood protection, and erosion regulation, as well as increasing demand for these ecosystem services. This study took the four largest cities in the YRD region (each covered an area within a radius of 20-km from the urban center, see Fig. 1)—Shanghai (over 13.5 million population), Nanjing (6.5 million), Hangzhou (4.5 million), and Suzhou (3.5 million)—as examples to explore ecosystem services supply and demand dynamics in response to land use and cover change during 1985–2015.

2.2. Classification of land use and land cover

We used the national land use datasets, which were produced by the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences through interpretation of the Landsat TM or ETM images at a 30-m resolution, for classification of land use and land cover in the YRD region during the years 1985–2015. The overall accuracy of classification with ground-based survey data was over 85% (Liu et al., 2014). The four cities in the YRD region included 11 different land cover classes, as shown in Fig. 1: (1) urban areas: high-density and continuous built-up fabric; (2) rural settlements: low-density and discontinuous built-up fabric; (3) rice fields: irrigated croplands; (4) rainfed croplands: non-irrigated croplands; (5) orchards: lands for growing fruits, tea, mulberry, and tree seedlings; (6) forestland: woodland with tree canopy density above 10%; (7) shrubland: vegetation cover dominated by shrubs; (8) grassland: herbaceous cover with a minimum coverage of 5%; (9) barren land: lands with vegetation coverage below 5%; (10) wetlands: inland marshes and salt marshes; and (11) water bodies: