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RESEARCH ARTICLE

Analyzing the spatial patterns and drivers of ecosystem services in rapidly urbanizing Taihu Lake Basin of China

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Abstract Quantifying and mapping the distribution patterns of ecosystem services can help to ascertain which services should be protected and where investments should be directed to improve synergies and reduce trade-offs. Moreover, the indicators of urbanization that affect the provision of ecosystem services must be identified to determine which approach to adopt in formulating policies related to these services. This paper presents a case study that maps the distribution of multiple ecosystem services and analyzes the ways in which they interact. The relationship between the supply of ecosystem services and the socio-economic development in the Taihu Lake Basin of eastern China is also revealed. Results show a significant negative relationship between crop production and tourism income ($p < 0.005$) and a positive relationship between crop production, nutrient retention, and carbon sequestration ($p < 0.005$). The negative effects of the urbanization process on providing and regulating services are also identified through a comparison of the ecosystem services in large and small cities. Regression analysis was used to compare and elucidate the relative significance of the selected urbanization factors to ecosystem services. The results indicate that urbanization level is the most substantial factor inversely correlated with crop production ($R^2 = 0.414$) and nutrient retention services ($R^2 = 0.572$). Population density is the most important factor that negatively affects carbon sequestration ($R^2 = 0.447$). The findings of this study suggest the potential relevance of ecosystem service dynamics to urbanization management and decision making.

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1 Introduction

The United Nations predicts that the world's urban population will reach 5 billion by 2030 (UN, 2010). Nearly half of this global urban expansion is expected to occur in Asia, particularly in China and India, accounting for 55% of the region's total population (Seto et al., 2012). Any strategy of sustainable development in the context of urban expansion therefore requires a sophisticated understanding of social, economic, and ecological processes and their relationships. Achieving a balance between conservation and development becomes an urgent need, as was emphasized by the Brundtland Commission, the Rio Declaration in 1992, the conventions on biologic diversity and climate change, and the Millennium Ecosystem Assessment (MEA, 2005). The ecosystem services approach provides a comprehensive way of understanding and alleviating the adverse effects of urbanization on the ecosystem.

A number of scientists have begun to grapple with the negative effects of anthropocentric activities on the ecosystem, primarily by implementing a rapidly growing array of projects that focus on ecosystem services (Daily et al., 1997; Naidoo et al., 2008; Nelson and Daily, 2010; Seppelt et al., 2011; Robertson, 2012). Ecosystem services refer to the benefits that humans receive from ecosystems (MEA, 2005). Humans are considered as part of the social-ecological system, because if the human element is removed, we have no services to speak of. Furthermore, humans modify ecosystems to enhance the production of specific services. The ecosystem service approach provides a new platform for engaging with the ongoing challenge of

aligning ecosystem conservation with social development (Tallis et al., 2009). At the same time, mainstreaming ecosystem services into policy and decision making is also dependent on the availability of spatially explicit information on the state of current ecosystem services (Cowling et al., 2008; Maes et al., 2012). Conservation organizations that focus on modeling ecosystem services, such as the Natural Capital Project and the Ecosystem Services Partnership, have been established. The purpose of managing multiple ecosystem services is to enhance the provision of specific services, some of which, such as food and timber, have led to the degradation of nutrient cycling, flood regulation, and recreation services (Rodriguez et al., 2006; Bennett and Balvanera, 2007).

Identifying where certain ecosystem services of interest are located in the typology with respect to other multiple services will improve our understanding of where to invest and where to preserve to maximize synergies or reduce trade-offs (Bennett et al., 2009). Thus, understanding the spatial discrimination of the same ecosystem services and the trade-offs between different ecosystem services is essential for the development of landscape-level conservation and management plans. Some innovative research has been conducted to illustrate how ecosystem services directly interact, or appear to do so, through the effect of a shared driver; changes in the provision of these services are affected by anthropogenic factors, such as changes in land use and land cover caused by socio-economic activities (Engel et al., 2005; Gordon and Enfors, 2008; Ricketts et al., 2008; Volante et al., 2012). However, theories on and general rules of the relationship between ecosystem services remain limited, particularly in areas that are undergoing rapid urbanization. Thus, identifying the main disturbance and stress factors and quantifying their effects become necessary.

Unprecedented urbanization has occurred over the past 20 years in China, particularly in the eastern area. This trend is expected to remain unchanged for the next two decades (Gong et al., 2011; Li et al., 2011; Zhu et al., 2011). The result of this dramatic transformation is a series of devastating consequences for both the environment and the ecosystem. The degradation of the ecosystem and ecosystem services has proven to be related to this rapid urbanization process (Du et al., 2010; Li et al., 2010a, b; Gong et al., 2013a). A range of demographic and socio-economic processes drive the changes in the demand and utilization of ecosystem services (Nelson et al., 2006; Costanza et al., 2007; Chen et al., 2012; Gong et al., 2013b). Quantitatively evaluating and assessing the delivery of ecosystem services and analyzing their interactions at the landscape level are determinants for implementing the ecosystem service approach in conservation (Metzger et al., 2006; Naidoo and Ricketts, 2006; Chisholm, 2010; Raudsepp-Hearne et al., 2010; Lautenbach et al., 2011). Therefore, analyzing the supply of ecosystem services and the relationship between such services and the social development in rapidly urbanizing areas is extremely necessary (Nelson et al., 2009; Willemen et al., 2010). Moreover, examining the relationship between ecosystem services and urbanization indicators is critical for achieving a balance between development and conservation.

InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) was developed by the Natural Capital Project based on ecological production functions (http://www.naturalcapitalproject.org/). It consists of a suite of models that utilize patterns of land use and land cover (LU/LC) to calculate and visualize the level and economic values of ecosystem services, including carbon sequestration (Schuman et al., 2002; Ruesch and Gibbs, 2008), biodiversity conservation (Wilcove et al., 1998; Ricketts, 2001; Nelson et al., 2008), water purification (Reckhow et al., 1980; UusiKamppa et al., 1997), recreation, and soil conservation. This tool has been applied to more than 20 major projects worldwide. This extensive application has contributed to revealing diverse services provided by nature, manifesting trade-offs between alternative development scenarios, and helping people make informed decisions on how to use natural capital (Carpenter et al., 2012; Daily et al., 2013).

The Taihu Lake is the third largest freshwater lake in China, and the Taihu Lake Basin is a significant ecological area in the eastern region of the nation. According to the Statistical Database of National Bureau of Statistics of China, the basin nurtured more than 3.7% of the total population, and created 11.6% of the gross domestic product (GDP) in 2007. It has become one of the most developed areas in China, with a distinctive social-ecological system. Since the 1980s, tremendous quantities of pollutants resulting from urbanization and economic development have been discharged into the rivers and lakes in this area. The demand for land has caused deterioration to the ecosystem, especially the aquatic ecological system (Shao et al., 2006; Xin and Stone, 2010).

In this study, we have applied the InVEST model and local statistics to study the Taihu Lake Basin area, which has been undergoing rapid urbanization. Our goal is to (i) disclose the spatial distribution of multiple ecosystem services and the interactions between them, and (ii) reveal the relationship between the supply of ecosystem services and the socio-economic development indicators in areas undergoing rapid urbanization.

2 Study areas and methodology

2.1 Study area

The entire Taihu Lake Basin is known as the core area of the Yangtze River delta, with the total area covering up to 3.69×10^4 km^2. It includes southern Jiangsu province, Jiaxing City, Huzhou City, part of Hangzhou City in

Zhejiang province, a small part of the Anhui Province, and most of Shanghai City. Situated in the subtropical zone, the Taihu Lake Basin has a typical subtropical monsoon climate in the south and a warm moist monsoon climate in the north. It is typically characterized by mild weather with moderate rainfall and a clear distinction among the four seasons. The mean annual rainfall is approximately 1,177 mm, and the annual average temperature is 14.9°C to 16.2°C.

Figure 1 shows that the selected area of the Jiangsu section of the Taihu Lake Basin is located at the bottom of the province and extends between 23°68′N, 23°68′E, and 23°68′N, 23°68′E. It covers an area of 1.94×10^4 km^2 and accounts for about 52.6% of the entire Taihu Lake Basin. The prominent geomorphic features of the region include crisscrossing patterns of numerous river nets and extensive lake areas, where the water surface accounts for 30% of the total proportion of the area.

The extraordinary geographical position and environment of Taihu Lake Basin have proven favorable for socio-economic development. The Jiangsu section of Taihu Lake Basin has a crucial function in the socio-economic development of Jiangsu province and also all of China. The 2010 statistical report for Jiangsu province showed that the population and GDP of the Jiangsu section of Taihu Lake Basin was 16.8133 million and 1,637 billion CNY, respectively. Its GDP accounted for approximately 4.8% of the whole for all of mainland China in the same year. There are many reasons why this area is of great importance to China. It is a valuable ecological area for providing wildlife habitats, maintaining a balance for the nutrient cycle and regulating climate change, etc. In addition, Taihu Lake is the critical drinking water resource for the surrounding cities, including Wuxi, Suzhou, and Shanghai. Its water is also used for industrial and agricultural purposes. In relation to the increasing economic significance and extensive population density, the water quality has experienced significant deterioration in recent years. The urban expansion has caused an enormous transition of land use and land cover in this region, while pollution and land use conversion have affected the habitats of various species, agriculture production, and pollutant purification (Guan et al., 2011). Therefore, spatially visualizing the ecosystem services and identifying the spatial pattern would assist in the ecological and environmental protection of the area. In addition, analyzing how the urbanization process influenced the provision of ecosystem services would support the sustainable development of the region.

2.2 Methodology

2.2.1 Data resources

Land use data for the year 2010 were derived from the National R&D Infrastructure and Facility Development Program of China: Data Sharing Infrastructure of Earth System Science — Data Sharing Centre of the Yangtze River Delta (http://nnu.geodata.cn). A section of the 2010 land use map of China was used. It was interpreted from Landsat TM images obtained in October 2010. All images were processed using ArcGIS10.0 software (ESRI, Inc., Redlands, CA). The main procedures used included geometric correction and human-machine interactive classification. These images of each county were rectified to the WGS_1984 datum and Albers conical equal area projection coordinated system based on the images in the corresponding region in 2008. The root mean square error was less than one pixel. The nearest-neighbor algorithm was used to resample all the images to a spatial resolution

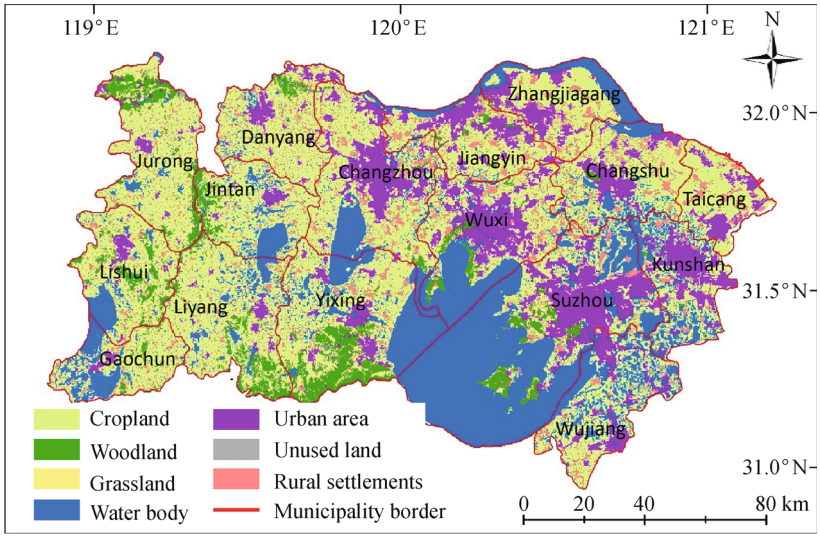

Fig. 1 Land use map (2010) of study area. Source: National R&D Infrastructure and Facility Development Program of China (http://nnu.geodata.cn).

of 30 m. Different land use types were then categorized by using human-machine interactive classification. Finally, seven land use types were identified: urban area (including residential, mining, commercial, and transportation), rural settlements, woodland, cropland, grassland, water body, and unused land. The classification accuracy was evaluated by means of the colorful aerial photography from 2010, and then integrating it with field verification for some complex land use areas. Results demonstrated that the overall classification accuracy was at least 90% for each land use type. The land-use map and the InVEST models were processed using the 30 m×30 m resolution data.

The municipal boundaries were acquired from the National Geomatics Centre of China (http://nfgis.nsdi.gov.cn), with the area of each municipality calculated based on these boundaries. The digital elevation model data for calculating nutrient retention were downloaded from the website of the International Scientific Data Service Platform (http://datamirror.csdb.cn/). The precipitation, evaporation, soil depth, and soil water content data in 2010 came from the website of the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do).

2.2.2 Quantification and analysis of ecosystem services

2.2.2.1 Selection of ecosystem services, indicators, and data specifications

Crop, aquatic, and meat production were selected to represent the local provision of services in each administrative district. In addition, tourism income was selected to describe cultural services. These data were gained from the statistical yearbook from each municipality (Table 1). Habitat quality represented the biodiversity-supporting services, and carbon sequestration and nutrient retention represented the regulating services. The values for these three ecosystem services were generated from the InVEST model, which was based on land use and land cover data and a series of parameters of the study area. All the parameters were either obtained from local statistics or from other scholars' study results from and were then calibrated before use.

Table 1 Ecosystem services analyzed in the study area

Ecosystem services	Unit	Quantification method
Provisioning service	–	–
Crop production (CP)	t/km^2	Municipality statistics yearbook
Aquatic production (AP)	t/km^2	Municipality statistics yearbook
Meat production (MP)	t/km^2	Municipality statistics yearbook
Cultural service		
Tourism income (TI)	B CNY/km^2	Municipality statistics yearbook
Supporting service	–	–
Habitat quality (HQ)	n (Relative value)	InVEST model
Regulating service	–	–
Carbon sequestration (CS)	t/km^2	InVEST model
Nutrient retention (NR)	kg/km^2	InVEST model

2.2.2.2 Carbon sequestration

We quantified four carbon pools — aboveground biomass, belowground biomass, soil, and dead organic matter — in the entire study area. We estimated carbon stocks in different land use and land cover categories of the landscape for the year 2010 (Table 1). Reaping rice, the main crop of the area, produces a portion of the methane (CH_4) emissions that lead to global warming. This study does not consider methane emissions in calculating carbon sequestration because the main purpose of the study is to obtain the relative value of selected ecosystem services and to compare them.

Aboveground biomass estimates were calculated using the data from the IPCC guidelines (Fang et al., 1996; Piao et al., 2009; Chuai et al., 2011). By using the same data source, belowground biomass and carbon stored in dead organic matter were respectively calculated using the ratio of root-to-shoot biomass and the estimates of the carbon in leaf litter for subtropical zone ecosystems. Zero or downscaled values were assigned to carbon stored in dead organic matter in human-modified forest or bare land uses. The carbon stored in the soil was estimated using the data given by Chuai et al. (2011).

2.2.2.3 Biodiversity conservation: habitat quality

We used the "habitat quality" model in InVEST to assess the habitat quality of the study area in 2010 (Table 1). This model combines information on LU/LC and threats to biodiversity to determine habitat quality and rarity and to generate habitat quality maps that serve as proxies for the status of biodiversity in a given region (Nelleman et al., 2001; McKINNEY, 2002; Forman et al., 2003).

A relative habitat suitability score ranging from 0 to 1 (1 indicates the highest habitat suitability) was assigned to each LU/LC type. A ranking of less than 1 indicates a habitat in which a species or functional group may have a relatively low survivability (Prugh et al., 2008; Franklin and Lindenmayer, 2009). The wetland and water body play an essential role in the study area according to the National Second Survey of Wetland Resources Report of China. Therefore, they were given the highest suitability score, followed by forest and grass lands; other LU/LC types were assigned 0 values. The sources of threats to wildlife and their habitat include various human activities, such as towns and rural settlements, plantations, and roads. We did not take three sources of habitat degradation and their impact on wildlife into consideration in this study, for which spatially explicit data were obtained: urban build-up

area, rural settlements, and agricultural areas. The relative impact of each threat on the habitats ranges from 0 to 1. The value expresses the extent of equal disturbance caused by a threat on a nearby habitat. Other input values, such as the impact distance of a specific threat and the relative sensitivity of each habitat type to each threat, depended on the actual conditions of the study area. The value of the habitat quality for each parcel was calculated after running the model. A good quality habitat indicates that the area is suitable for the species under analysis and suggests potential for biodiversity conservation, but does not necessarily confirm the presence of the species (Nelson et al., 2008).

2.2.2.4 Water service models: water production and water purification

InVEST (Tallis et al., 2009) was employed to model the annual average water yield and calculate the annual average nitrogen retention in the study area to reflect the water purification services provided by the basin and by each municipality in 2010 (Table 1). The discharge of total nitrogen into the local watershed was used as a measure of the water pollution and proxy for nonpoint-source pollution.

The output amount of nitrogen was calculated according to the land-use type. The municipalities' 2010 statistical yearbook provided the output values for the urban area, rural settlements, and cultivated land, while published references made the input values for other land-use types available (Li et al., 2008; Li et al., 2010b).

2.2.2.5 Analysis of the distribution and interactions of ecosystem services

The individual ecosystem services for each of the 16 municipalities were computed and mapped in ArcGIS to visualize and compare their spatial patterns. Correlations between pairs of ecosystem services were obtained through correlation analysis by SPSS 18.0. The correlations were analyzed using the Pearson parametric correlation test.

2.2.3 Analysis of the interactions of ecosystem services and selected indicators

Research was conducted in 16 municipalities, with the goal of examining the relationships betweem the seven types of ecosystem services and urbanization indicators. The ten indicators shown in Table 2 were adopted to represent the urbanization status of each municipality, including the following: ratio of urban area (RUA), density of gross domestic production (DGDP), gross industry output value (GIOV), second industry output value (SIOV), third industry output value (TIOV), population density (PD), ratio of second industry (RSI), ratio of third industry (RTI), ratio of urbanization (RU), and ratio of natural capital (RNC). These indicators were selected to represent the status quo of the cities under consideration, where the values were drawn from the statistical yearbook of each municipality.

Each ecosystem service and indicator value for each district (city and county) was normalized between 0 and 1, after which the normality test was conducted. The Pearson parametric correlation test was then performed to determine the interactions between the ecosystem services and selected indicators. The correlation coefficients reflect linear relationships, but Table 4 shows several kinds of correlations between different indicators, so that uncertainty may exist in explicating the effects of the selected indicators. A PCA analysis was accordingly executed to ascertain the significant factors. Based on the correlation (Table 4) and PCA analysis results (Table 3), four factors (DGDP, SIOV, PD, and RU) were used to reflect the distinct socio-economic dimensions. The four variables

Table 2 Selected indicators of urbanization

Abbr.	Description	Unit	Min	Max	Mean	Std. Deviation
RUA	Ratio of urban area	%	3.44	30.76	14.34	9.12
DGDP*	Density of gross domestic production	B CNY/km^2	17.68	236.05	105.44	77.89
GIOV	Gross industry output value	B CNY/km^2	43.46	702.24	250.06	202.06
SIOV*	Second industry output value	B CNY/km^2	9.76	143.40	6.19	45.92
TIOV	Third industry output value	B CNY/km^2	6.21	84.48	38.09	27.62
PD*	Population density	N/km^2	422.00	2155	1100	584.00
RSI	Ratio of second industry	%	52.82	64.08	57.54	2.79
RTI	Ratio of third industry	%	31.20	46.10	38.19	3.95
RU*	Ratio of urbanization	%	45.00	100.00	63.02	15.10
RNC	Ratio of natural capital (including water body, forest, and grassland)	%	11.00	77.00	30.05	17.61

Note:* Variables used in linear regression models; B means billion.
Source: Nanjing statistical yearbook (2011); Zhenjiang statistical yearbook (2011); Suzhou statistical yearbook (2011); Wuxi statistical yearbook (2011); Changzhou statistical yearbook (2011).

Table 3 Results of the principle component analysis (PCA) of the indicators, showing the principle component with an eigenvalue > 1

Abbr.	Component 1	Component 2
DGDP	0.990	0.043
SIOV	0.978	0.167
PD	0.972	−0.089
TIOV	0.956	0.184
GIOV	0.944	0.300
RUA	0.942	0.234
RU	0.815	−0.487
RTI	0.700	−0.655
RSI	0.057	0.927
RNC	0.012	0.342
Eigenvalues	6.731	1.859
Proportion	67.32	18.59
Cumulative	67.32	85.91

were subsequently adopted in the final linear regression models to reveal the relative extent to which each of the indicators affect the ecosystem services (Gong et al., 2013b).

3 Results

3.1 Spatial patterns of individual ecosystem services

Figure 2 mapped all seven ecosystem services in each district. Limited by the level of statistics, the results of the model calculation were on a county basis. The total value of each service in every municipality was chosen to reflect the distribution of the ecosystem services in the whole area. The mapping of the geographic distribution of the provision for each ecosystem service demonstrated a totally distinct and individual pattern.

In regard to the provision services for Taihu Lake, the western municipalities provided more crop-production services than the other municipalities, and the districts around the lake had a high supply of aquatic production services. Meat production was combined in the northwestern areas of the Lake, and tourism income was centered in the region. The best habitat quality score for the central area of the Taihu Lake generally exhibited a declining trend as the distance from the lake decreased. Carbon sequestration and nutrient retention services demonstrated a similar spatial distribution pattern, whereas the intermediary areas had relatively high regulating services.

Figure 2 shows that the crop and meat production services east of the Taihu Lake are essential to the whole area, requiring strict protection of the crop land. The northeastern area contributes substantially to the nutrient retention and export services. It is necessary, therefore, that a more efficient use of fertilizer be implemented. The region around the lake also supplies the majority of the aquatic products for the area, thus requiring that the quality control of the water be protected and improved. Moreover, the body of the Taihu Lake must be rigorously safeguarded due to its critical function in providing habitats for biodiversity. As for cultural services, it was determined that the cities of Wuxi, Changzhou, and Suzhou protect their natural capital to exploit their locational advantages. Other cities should also explore the tourism and cultural values of their natural capital.

At the city scale, the 16 cities were divided into three clusters according to population size. The first cluster, representing small cities, included Lishui, Gaochun, Jintan, Jurong, Taicang, Danyang, and Liyang, all of which had populations below one million. The second cluster, which represents medium-sized cities, consisted of Yixing, Zhangjiagang, Wujiang, Changshu, Jiangyin, and Kunshan, all of which had populations between one and three million. The third cluster was comprised of the three largest cities, Changzhou, Wuxi, and Suzhou, each of which had a population of more than three million. The mean value of each service for every municipality was then mapped to compare the provision of ecosystem services in the different cities (Fig. 3) and to indicate the average value of the ecosystem services of each city cluster (Fig. 4).

Figures 3 and 4 illustrate that the importance of the crop and meat production services diminished as the city size increased. The aquatic production services, which were limited by natural conditions, did not exhibit the same trend. The tourism income generally rose sharply with an increase in the urban size. In contrast, there was a noticeable decrease in carbon sequestration and nutrient retention. Habitat quality was exceedingly low in nearly all cities, with the exception of Suzhou.

3.2 Interactions among ecosystem services

Most of the ecosystem services interact with one another (Table 4). With the exception of a pairing of crop production and tourism income which had a negative relationship, the correlations between the five pairs of ecosystem services were highly positive. The three intensively managed provision services — crop, aquatic, and meat — demonstrated no correlation, but crop production presented a high number of positive correlations with carbon sequestration and nutrient retention. Aquatic production was positively correlated with habitat quality, and meat production was positively correlated with regulating service — nutrient retention. Carbon sequestration was similarly significantly correlated with nutrient retention.

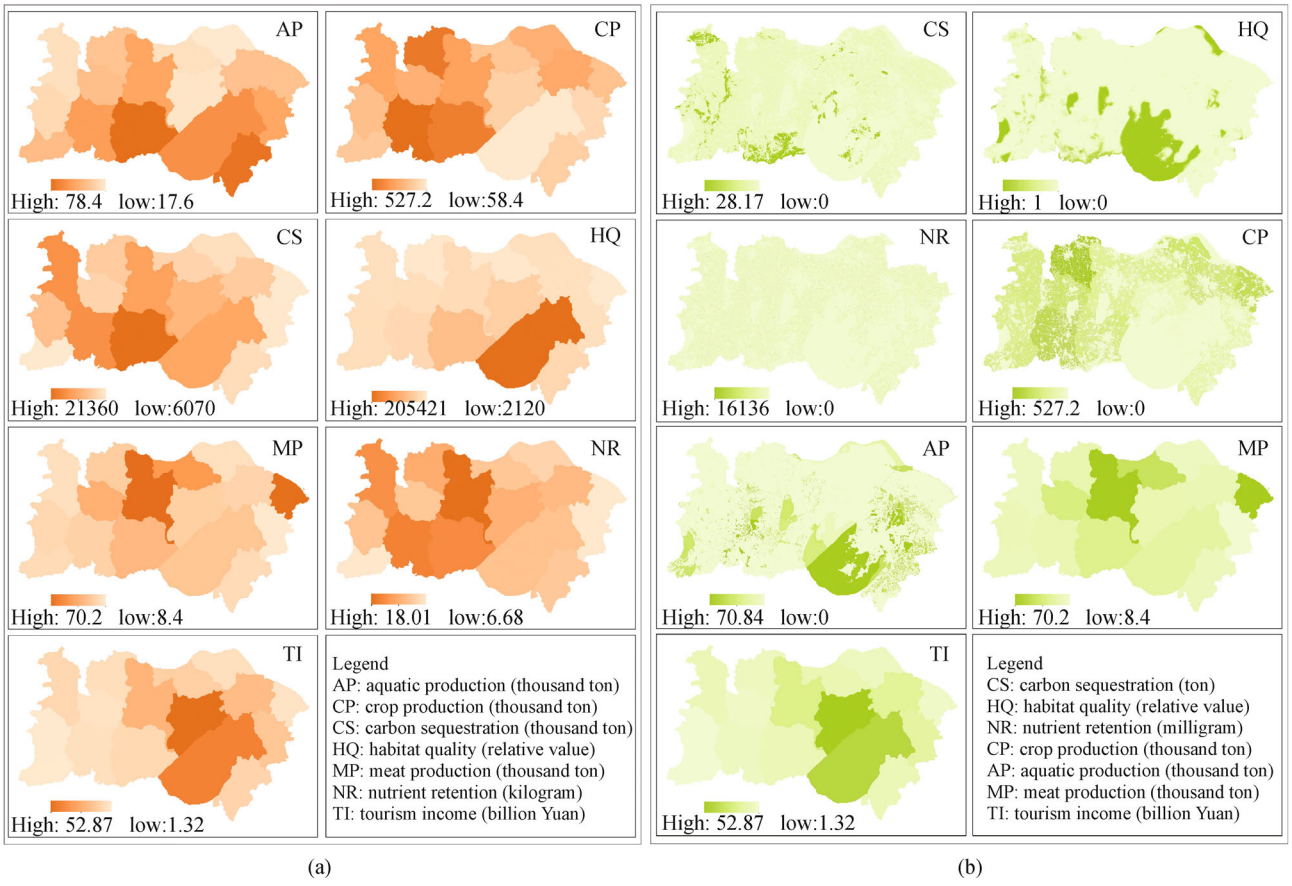

Fig. 2 (a) Total values of the seven ecosystem services in each municipality and (b) spatial distribution the of seven ecosystem services in the study area.

3.3 Relationship between the ecosystem services and urbanization indicators

The correlation coefficients between the ecosystem services and selected indicators are shown in Table 4. A highly negative correlation existed between RUA, DGDP, SIOV, PD, RU, and crop production service, and a prominent inverse correlation between RNC and aquatic production. Tourism income exhibited an obvious direct correlation with RUA, DGDP, GIOV, SIOV, TIOV, PD, RTI, and RU at the 0.01 level, and its correlation coefficient with RU was the highest among the others. Regulating services, carbon sequestration, and nutrient retention exhibited notable inverse correlations with several of the indicators, including DGDP, SIOV, PD, and RU. Carbon sequestration was also negatively correlated with RUA, GIOV, and TIOV. Unlike the above-noted services, habitat quality was positively only when related with RNC.

Given that obvious positive correlations existed among the four indicators (DGDP, SIOV, PD, and RU), the linear regression model was employed to identify the cardinal elements that affect the provision of ecosystem services. A comparison of R^2 value determined the relative significance of the four factors to the ecosystem services CP, CS, and NR. Table 5 shows the intriguing outcome: the ratio of urbanization was the most substantial factor, and it was inversely correlated with crop production and nutrient retention services. By contrast, population density was the most important component that negatively affected carbon sequestration. DGDP and SIOV produced nearly the same reverse effect on carbon sequestration. The standardized regression equation was expressed as: CP = 529.05–0.119RU (R^2 = 0.414); NR = 15.582– 10.479*RU (R^2 = 0.572); CS = 1.132–0.001*PD (R^2 = 0.447).

4 Discussion

4.1 Ecosystem services: spatial patterns and interactions of ecosystem services

Ecosystem services are intimately associated with social, ecological, and geographic factors that determine the concentration of human activities and are interrelated with the ecosystem services in specific areas of the landscape (Raudsepp-Hearne et al., 2010). This study found elevated

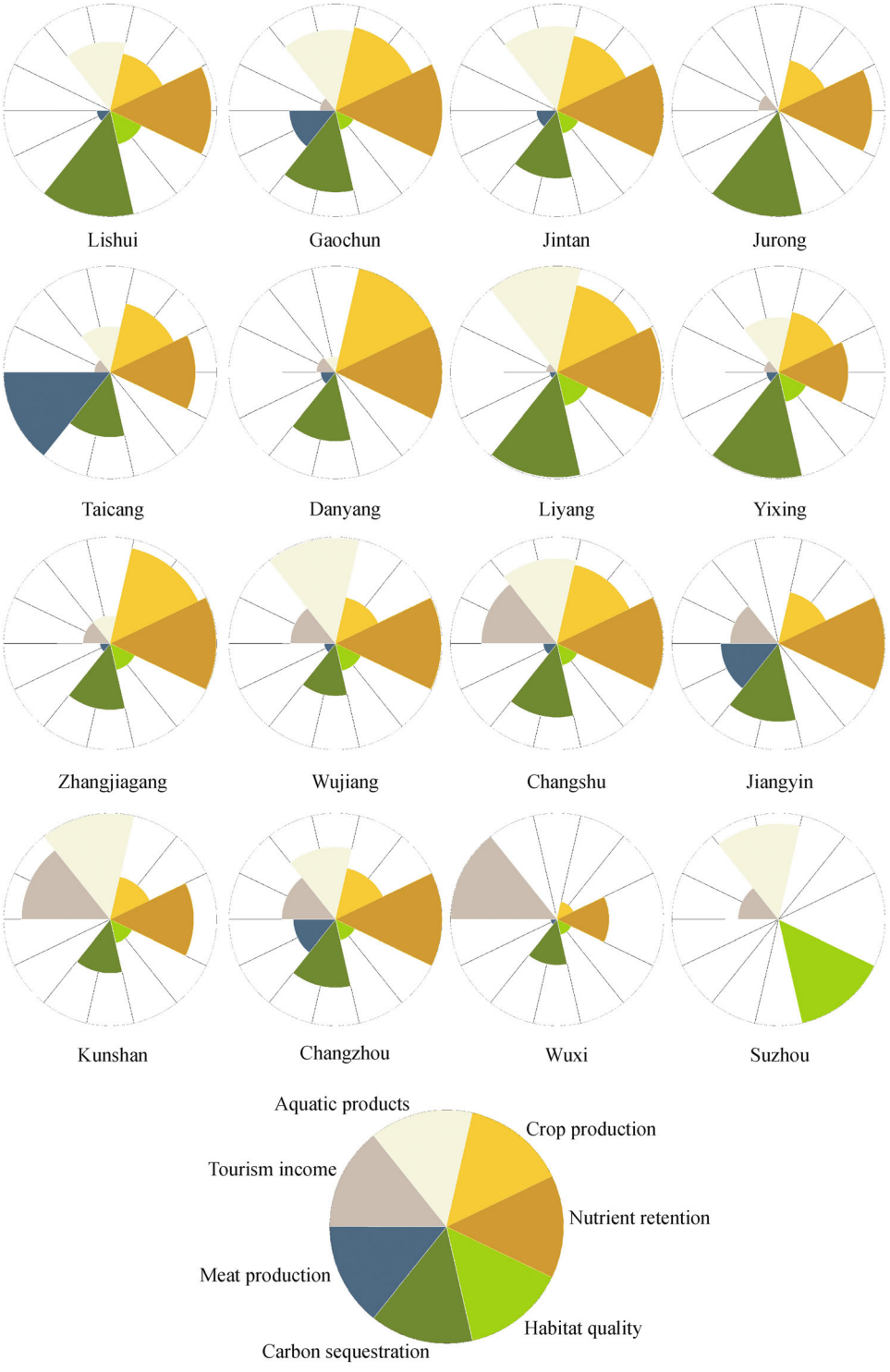

Fig. 3 Ecosystem services in each municipality. The mean value of each of the ecosystem services is illustrated by the petal length, and the municipalities are ordered by population size.

crop production located in cities with a flat topography and a low ratio of urbanization, such as the areas west and north of the Taihu Lake (Fig. 2). These cities are the most important agricultural towns in the region and have a crucial function in the food chain. An increase in the urban size and ratio of urbanization has, however, resulted in a

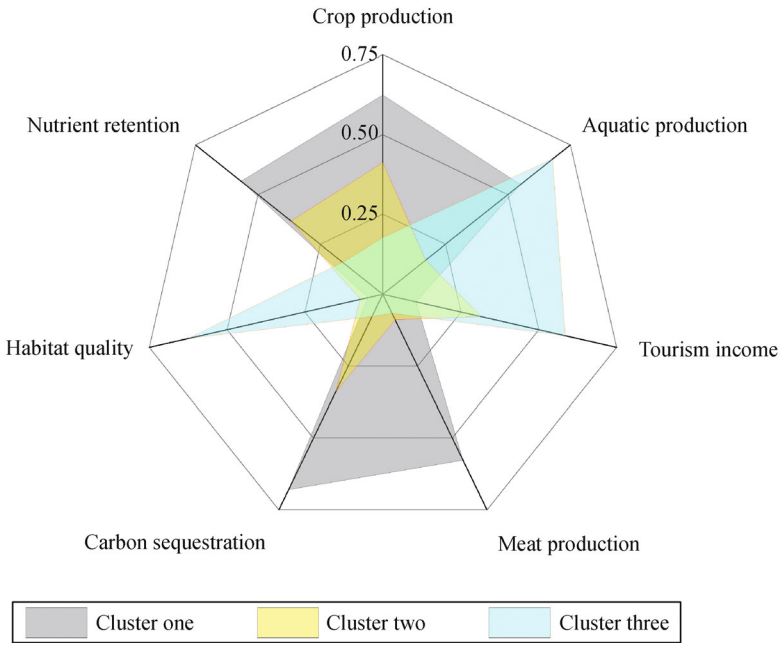

Fig. 4 Average value of each studied ecosystem service in the three city clusters, respectively. Cluster one includes the cities with a population of less than one million, cluster two includes cities with a population between one and three million, and cluster three, cities with a population of more than three million.

dramatic decrease in the provision of crop production (Fig. 4). Many reasons may be attributed to this consequence, but the set of changes resulting from urban expansion are the principal causes. Urban expansion usually occurs on cultivated lands, particularly in the coastal and central provinces, which results in a decrease in crop production (Long et al., 2009). Livestock is strongly affected by social demand and economic policies, whereas aquaculture is influenced by the local geographic conditions in the studied area. Meat and aquatic production do not illustrate any obvious rule in spatial supply or interactions with urban size (Fig. 4). Tourism income represents a typical trait, given that big cities remain at the top of tourism destinations. Changzhou, Wuxi, and Suzhou indicated the highest tourism function values within the study area, which was identical to the biodiversity supporting function exhibited by the habitat quality (Fig. 2). Habitat quality owes much to the multitude of lakes in the three cities. This relation illustrates that lakes and wetlands have a prominent role in the biodiversity support of the area. The habitat quality in both medium and small cities is confronted with a severe situation caused by rapid urbanization (Gong and Wu, 2014). Carbon sequestration rates are low and are concentrated in the southern and central parts of the study area. The agricultural soil and city carbon sinks under these conditions can be particularly important for maintaining sustainable development (Nowak, 1993; Piao et al., 2009; Poudyal et al., 2010; Munoz-Valles et al., 2013). Nutrient retention displays a distribution pattern similar to that of carbon sequestration. Such characteristics are typical of high forest coverage rates and major grain production. The cultivated land retains a great quantity of imported fertilizer, but the nutrient elements, particularly nitrogen sourced from agriculture, have become key factors that cause eutrophication in Taihu Lake (Tian et al., 2011; Li et al., 2010b), a situation that is progressively becoming more serious. The natural forest and grass lands, forests, or artificial vegetation buffer belt in farmland areas retain the nutrient elements and thereby eliminate the nitrogen and phosphate pollutants in the surface runoff; vegetation buffer zones should therefore be designed to alleviate the eutrophication of water bodies in the area (Weigelhofer et al., 2012).

The interactions between ecosystem services have been explicated in this work (Table 4). The sole negative relationship was observed between crop production and tourism income, a result consistent with the observation that tourism income is highly localized in a large city, such as Suzhou, Wuxi, and Changzhou. The result is indicative of the weak cultural and aesthetic functions exerted by natural systems in small cities. The positive relationship between aquatic production and habitat quality similarly indicates the significance of lakes in supporting biodiversity and providing aquatic products. The positive correlations between carbon sequestration, crop production, and nutrient retention exemplify the active role that agricultural production has in carbon sink and nutrient retention. Intensified agricultural development following the excessive application of fertilizers have, however, caused an

Table 4 Correlation coefficients between the ecosystem services and selected indicators

	CP	AP	MP	TI	CS	HQ	NR	RUA	DGDP	GIOV	SIOV	TIOV	PD	RSI	RTI	RU	RNC
CP	1																
AP	−0.1	1															
MP	0.415	−0.365	1														
TI	−0.527*	−0.12	−0.277	1													
CS	0.604*	−0.353	0.364	−0.493	1												
HQ	−0.232	0.515*	−0.426	−0.352	−0.152	1											
NR	0.732**	−0.347	0.518*	−0.364	0.763**	−0.432	1										
RUA	−0.509*	−0.259	−0.026	0.787**	−0.504*	−0.368	−0.415	1									
DGDP	−0.538*	−0.053	−0.156	0.803**	−0.704**	−0.159	−0.588*	0.906**	1								
GIOV	−0.474	−0.059	−0.165	0.808**	−0.619*	−0.212	−0.482	0.906**	0.974**	1							
SIOV	−0.529*	−0.068	−0.138	0.791**	−0.695**	−0.191	−0.568*	0.918**	0.991**	0.982**	1						
TIOV	−0.444	−0.194	−0.009	0.787**	−0.610*	−0.262	−0.462	0.921**	0.965**	0.959**	0.971**	1					
PD	−0.578*	0.018	−0.199	0.818**	−0.685**	−0.04	−0.575*	0.867**	0.971**	0.949**	0.952**	0.927**	1				
RSI	0.088	0.212	0.024	−0.222	−0.166	−0.029	0.044	0.135	0.015	0.112	0.097	0.097	−0.038	1			
RTI	−0.285	−0.218	0.074	0.630**	−0.258	−0.029	−0.294	0.524*	0.638**	0.588*	0.576*	0.621*	0.706**	−0.568*	1		
RU	−0.615*	0.206	−0.386	0.833**	−0.699**	0.035	−0.620*	0.770**	0.887**	0.879**	0.859**	0.812**	0.948**	−0.063	0.667**	1	
RNC	0.191	−0.662**	0.376	0.058	0.211	−0.809**	0.418	0.062	−0.094	−0.056	−0.05	0.012	−0.213	−0.032	−0.1	−0.294	1

Note: $^{**}p < 0.01$ (two tailed), $^{*}p < 0.05$(two tailed).

Table 5 Linear regression results of the selected indicators and ecosystem services

Service	Indicator	Unstandardized Coefficients		Adjusted R^2	Standardized coefficients (Beta)	t	Sig.
		B	Std. Error				
CP	Constant	312.827	38.647	0.300	−0.589	8.095	0.000
	DGDP	−81.276	29.813			−2.726	0.016
	Constant	308.596	39.414	0.268	−0.562	7.830	0.000
	SIOV	−131.660	51.729			−2.545	0.023
	Constant	358.394	46.436	0.377	−0.647	7.718	0.000
	PD	−0.119	0.038			−3.177	0.007
	(Constant)	529.050	91.008	0.414	−0.673	5.813	0.000
	RU	−479.045	140.662			−3.406	0.004
CS	Constant	1.057	0.064	0.443	−0.693	16.384	0.000
	DGDP	−0.179	0.050			−3.593	0.003
	Constant	1.049	0.066	0.407	−0.668	15.814	0.000
	SIOV	−0.292	0.087			−3.358	0.005
	Constant	1.132	0.082	0.447	−0.696	13.834	0.000
	PD	0.001	0.001			−3.624	0.003
	(Constant)	1.421	0.173	0.394	−0.695	8.208	0.000
	RU	−0.877	0.268			−3.277	0.006
NR	Constant	10.591	0.738	0.293	−0.583	14.346	0.000
	DGDP	−1.530	0.570			−2.687	0.018
	Constant	10.465	0.762	0.241	−0.540	13.728	0.000
	SIOV	−2.404	1.001			−2.403	0.031
	Constant	11.209	0.944	0.288	−0.579	11.873	0.000
	PD	−0.002	0.001			−2.657	0.019
	Constant	15.582	1.479	0.572	−0.775	10.534	0.000
	RU	−10.479	2.286			−4.583	0.001

Note: CP, CS, and NR refer to crop production, carbon sequestration, and nutrient retention, respectively. RU and PD refer to the ratio of urbanization and population density, respectively.

increase in the nutrient elements transported into rivers and lakes in the area. Cultivated land has thus been one of the leading causes of water pollution in Taihu Lake (Li et al., 2010a, b).

4.2 Relationship between ecosystem services and selected indicators

Examining the correlative factors of the provision of ecosystem services demonstrates the connection between society and the ecosystem and encourages the consideration of ecosystem conservation in urban development (Kareiva et al., 2007). Figure 4 indicates that urban size affects the supply of multiple ecosystem services. A comparison of the supply of such services across city clusters illustrates the dynamics of ecosystem services in the urbanization process. Increasing evidence reflects that the ecosystem service approach should be integrated into urban planning and decision making (Daily and Matson, 2008; Ervin et al., 2012). The results of the linear regression conducted in this paper provide proof of the inversely linear effect of urban expansion on crop production, nutrient retention, and carbon sequestration.

The most important service, crop production, is directly constrained by the area of the cultivated land. The results of the linear regression analysis of crop production and the selected indicators suggest that RU is the primary element with the highest negative influence. This relation implies that cities grow at the expense of cultivated land. Given that GDP and the ratio of urbanization have become the favored measure of local officials, an increasing number of cities are likely to urbanize (Jiang et al., 2012). The same situation is indicated by the relationship between nutrient retention and the selected indicators, which states that the urbanization process has not only caused an increase in the discharge of water pollutants, but has also led to the reduction of natural capital, which is mainly responsible for water purification. An intriguing result for carbon sequestration is that PD is the most significant factor. Forest land is apparently distributed close to small cities with low population density, while the forest coverage rate near large cities is incredibly slight.

Few studies investigating the impact of urbanization indicators on the supply of multiple ecosystem services have been conducted to date. The presented modeling approach contributes to the urban and social development process and explores sustainable urban planning and conservation options. Such an approach can assess the effect that different scenarios of city development can have on the future supply of ecosystem services. The analysis of the present study was grounded on the quantities of supply services from an ecosystem model and statistics, and was not explicitly based on the value of the services as in other studies (Turner et al., 2003; Zandersen and Tol, 2009). Economic data can thus be added in future studies, and the economic assumptions on the dynamics of the supply of ecosystem services must be evaluated to make the model suitable for supporting policy decisions on a city or basin scale.

5 Conclusions

The InVEST model and local statistics were applied to quantify the seven ecosystem services of the Taihu Lake Basin area. The mapping of ecosystem service patterns and the regression tests empirically demonstrated that massive urbanization had serious implications on the provision for ecosystem services, whether they be provision-services or regulating-services. The local government applied special stress on the construction of infrastructure and improvement of public facilities to pursue a high level of quality to the economy and urban development, yet ignored the protection of the ecosystem. It was inevitable that ecological conditions would deteriorate and the capability to provide ecosystem services would degenerate. The ecosystem services approach can help the government protect and restore ecological services in the region. Our results suggest that urban development should adopt an ecosystem-service strategy to align human well-being with conservation and to recognize the interaction between the ecosystem services and the forces of urbanization. The local government bureaus and planners should give greater attention to the application of ecosystem service theory and approach to enhance the capability of ecosystem services to provide and direct sustainable urban development. We have aroused the intrigue for developing and applying ecosystem service methods to urbanization and ecology protection.

Given that the quantitative and spatial visualization approaches are crucial for exploring the dynamic variation process of ecosystem services, detailed time series data and comprehensive quantification methods should be conducted to provide opportunities to explore the most effective way to assess and map the provision of ecosystem services and the demand for them. In this paper, only a few social or urbanization factors were integrated into the correlation analysis of ecosystem services and the social system. Additional ecosystem services (i.e., flood mitigation, crop pollination) and social indicators (i.e., land use change, landscape pattern indices) are needed to investigate the mechanism between them. An investigation of the trade-offs between multiple ecosystem services will be beneficial to the management of ecosystem conservation and urban development.

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