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Trade-offs and Synergies of Ecosystem Services in the Taihu Lake Basin of China

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Abstract: Understanding the spatial interactions among multiple ecosystem services is crucial for ecosystem services management. Ecosystem services, including crop production, freshwater supply, aquatic production, net primary production, soil conservation, water conservation, flood regulation, forest recreation, were measured at 1-km grid scale covering the Taihu Lake Basin (TLB) of China. Our objective is to get a comprehensive understanding of the spatial distributions, trade-offs, synergies of multiple ecosystem services across the TLB. Our results found that: 1) majority of ecosystem services were clustered in space and had a similar spatial distribution pattern with the geographical resource endowment. Most of the landscape contributed a high supply of no services, one or two, and a low supply of three to seven services. 2) There were high correlation between forest recreation and freshwater supply and regulating services. Aquatic production had low correlation with other services. 3) The changes of provisioning services led to trade-offs between regulating services and cultural services in the TLB, while synergies mainly occurred among the provisioning service. 4) The spatial relationships of multiple services are consistent at 1-km spatial scale, counties and provinces. This research could help integrate multiple ecosystem services across scales and serve as a reference for decision making.

Keywords: ecosystem services; spatial pattern; Principal Component Analysis; trade-offs; synergies; Taihu Lake Basin (TLB)

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1 Introduction

Ecosystem services are the resources derived from ecosystems (Costanza et al., 1997; MA, 2005). In recent years, ecosystem services have been widely used in land-use management, policy-support and human well-being (Goldstein et al., 2012; Bateman et al., 2013). Understanding the reciprocity of multiple ecosystem services has become a hotspot and frontier of sciences for sustainable development (Raudsepp-Hearne et al., 2010). There are six kinds of spatial relationships in different ecosystem services: synergies, win-no change, lose-no change, trade-offs, losses and no change (Bennett et al., 2009; Haase et al., 2012). While trade- offs and synergies are often key issues for policy-makers to consider (Turner et al., 2014).

Trade-off refers to when one ecosystem service increases, it leads to the weakening or decreasing among

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the other ecosystem services (Rodriguez et al., 2006). For instance, an increase in the supply of services to crop yields will lead to a corresponding decrease in forest and wetlands (Sayer and Cassman, 2013). Synergy means that multiple services have consistent trends that the increase of one service may also improve other services (Ricketts et al., 2004). For example, afforestation in appropriate area can improve regional provisioning, regulating and cultural services (MA, 2005). Human activities and socio-ecological interactions have changed the ecosystem structure and function, affecting ecosystem service trade-offs and synergies (Su et al., 2012a; Qiu and Turner, 2013). Urbanization and agricultural development leading to the degradation of forest and wetlands, changing the spatial distribution and related ecosystem services (Bateman et al., 2013). Therefore, it is essential for landscape designers to consider positive and negative interactions among ecosystem services in order to optimize the overall functionality of the ecosystem (Bennett et al., 2009).

The trade-offs and synergies of the ecosystem services are spatially connected and interdependent and therefore easily bundled together in a geographic unit (Raudsepp-Hearne et al., 2010). A bundled analysis can help landscape multi-function management and discern common trade-offs and synergies (Raudsepp-Hearne et al., 2010). More importantly, using the bundled ecosystem analysis can effectively describe individual service distribution pattern and treat the whole ecosystem as separate entity, avoiding repeated calculation of multiple ecosystem service effects (Raudsepp-Hearne et al., 2010). Based on the land use and ecosystem management policies, the impacts of ecosystem services on trade-offs and synergies under different scenarios were simulated to provide the basis for scientific policy-making (Bateman et al., 2013). The examples include biofuels, food crops, forestry, housing development and land use (Goldstein et al., 2012).

The Taihu Lake Basin (TLB) is located at the core of the Yangtze River Delta. In 1985–2010, TLB experienced a rapid economic growth (Gross Domestic Product, GDP) +15.7%/yr), population growth (+3.0%/yr on average), urbanization (+9.2%/yr on average) (Xu et al., 2016). Urbanization has rapidly changed the landscape pattern. In recent years, the degradation of ecosystem services in the TLB were remarkable, including the purification of water resources (Guo, 2007), carbon sequestration (Wang et al., 2016), water quality regulation (Yin et al., 2009), crop production (Liu et al., 2015). The degradation of ecosystem services has posed a threat to the region’s ecosystem safety and sustainability. According to the latest national urbanization plan (2014–2020), the future urbanization of the region will increase the demand for land resources and exert much pressure on the ecological environment support capacity (State Council of China, 2014). Therefore, there is an urgent need to explore the relationship among ecosystem processes in the TLB and to map the ecosystem services for decision-making of sustainable development (Fu et al., 2013). Previous studies have focused on the evaluation of a single ecosystem service in the TLB and its impact on land use change (Li et al., 2015). Some studied the concentration of pollutants and heavy metals in the TLB (Yu et al., 2012; Jiao et al., 2014; Xu et al., 2016). Few have studied the spatial distribution patterns of various services in the TLB and their interactions among different service spaces. Also there is no study on the trade-offs and synergies of different services or the strength of regional spatial associations of the services in the TLB. Moreover, the research units were mainly administrative divisions of cities and counties (Raudsepp-Hearne et al., 2010; Yang et al., 2015). None has used the 1-km grid cells as the analysis units.

In this research, the following scientific questions are put forward in the TLB: 1) Are the spatial distribution patterns of different ecosystem services consistent? 2) What are the interactions in space among ecosystem services? 3) How the ecosystem services are bundled and where are the strongest or weakest regional trade-offs and synergies? In the decision-making process, it is important to figure out the interrelationships of ecosystem services (weakening competition in ecosystem services and enhancing synergies) to keep the balance between resource consumption and resource conservation.

2 Materials and Methods

2.1 Study area

The Taihu Lake Basin is located at the Yangtze River Delta in eastern China (30°28′N–32°15′N, 119°11′E –121°51′E) (Fig. 1). The TLB is one of the most economically developed regions in China. Administrative divisions include Shanghai Municipality and the large

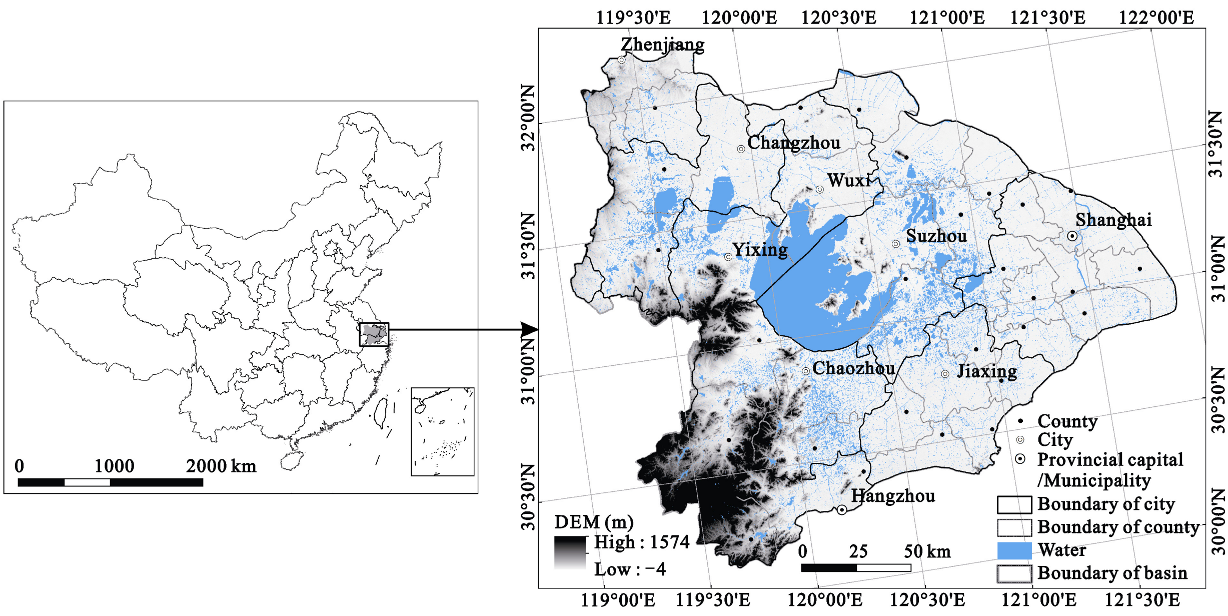

Fig. 1 Location of the Taihu Lake Basin in China

part of Jiangsu and Zhejiang provinces. The basin area is 36 900 km^2. The average elevation is 34.4 m, varying from –4 m to 1574 m. There are two types of landforms: mountain and plain. The mountains are in the southwest of the basin, while the plain is in the north, east and south of the basin, accounting for 80% of the basin area. The climate is subtropical monsoon, with an annual precipitation of 1010–1400 mm and an annual average temperature of 15.6℃. There are more than 200 rivers and 10 lakes (over 10 km^2) in the basin, whereby Taihu Lake (2427.8 km^2) is the largest lake in the basin and the third largest freshwater lake in China.

2.2 Quantifying ecosystem service

2.2.1 Provisioning services

Crop production. The TLB is China's most important granary. In 2010, the crop production accounts for 1.4% of the national total. However, since 1985, there has been a significant decline in its crop production (Xu et al., 2016). The crop production in the TLB decreased by 4.5 × 10^6 t from 1985 to 2010 (Xu et al., 2016). Crop production efficiency (crop production per unit area) is an important indicator of crop production in the farmland provisioning service. We use a crop productivity per unit area instead of crop production. It was computed by dividing crop production of each town by its area (Su et al., 2012a). We used rice, wheat and maize as the three major crops to calculate the crop productivities of counties in the TLB in 2010.

Freshwater supply. The river network of the TLB carries 1.76 × 10^{10} m^3 of freshwater annually downstream. However, due to the large population to be supported, the per capita local water resources is only 1/5 of the national average. Furthermore, the rapid urbanization led to the conversion of a large number of wetlands into urban and agricultural land. At the same time, there are greater freshwater demand by the rapid industrial development in the TLB. The total amount of water resources is an important indicator of freshwater supply service. we calculated the annual water yield via multiplying water production coefficient by the annual precipitation (Jin et al., 2009). The monthly precipitation of the 9 meteorological stations near the TLB were acquired from the China Meteorological Data Network, and the annual precipitation of each site in 2010 was calculated.

Aquatic production. Aquatic production refers to the catches of aquatic production, either cultivated or uncultivated. There are a variety of aquatic products due to the highly developed aquaculture in the TLB. Aquatic production not only provides products to human but also maintain ecosystem functions (Brauman et al., 2007). We used the aquatic production per unit area to measure the aquatic production service.

2.2.2 Regulating services

Net Primary Productivity (NPP). NPP is one of the significant regulating services of terrestrial ecosystem that has played a vital role in climate change (Piao et al., 2009). The Carnegie-Ames-Stanford Approach (CASA) model proposed by Potter (Potter et al., 1993) and Field (Field et al., 1995) was used to figure out NPP. The estimation of NPP is by two variables: photosynthetically active radiation (APAR) and light energy conversion (ε):

$$NPP(x,t)=\sum\left[APAR(x,t)\times\varepsilon(x,t)\right] \tag{1}$$

$$APAR(x,t)=SOL(x,t)\times FPAR(x,t)\times 0.5 \tag{2}$$

$$\varepsilon(x,t)=T_{\varepsilon 1}(x,t)\times T_{\varepsilon 2}(x,t)\times W_{\varepsilon}(x,t)\times\varepsilon^{*} \tag{3}$$

where $APAR$ (x, t) indicates the photosynthetically active radiation (MJ/m^2) absorbed by cell x in month t, and ε (x, t) indicates the actual light energy utilization. SOL (x, t) is the total solar radiation (MJ/m^2), and $FPAR$ (x, t) is the ratio of photosynthetically active radiation absorbed by plant. The constant 0.5 is the effective solar radiation (wavelength 0.38–0.78 μm) accounted for the proportion of the total solar radiation. $T_{\varepsilon 1}$ (x, t) and $T_{\varepsilon 2}$ (x, t) are the stress coefficients of the highest temperature and the lowest temperature, respectively. W_{ε} (x, t) refers to the water stress coefficient. ε^* refers to the ideal of different vegetation types. Maximum light energy utilization (default is 0.389 gC/MJ).

Soil conservation. Soil erosion is the main cause of degradation and loss of land resource (Li and Zhou, 2016). Soil conservation is the basic service function of ecosystem. The value of soil conservation was measured by the amount of soil erosion. The soil erosion is estimated by the Universal Soil Loss Equation (USLE) (Su et al., 2012a), which considers the rainfall factor, surface cover factor, soil erosion factor, soil conservation measure factor, topographic factor and land use type.

$$A_c=A_p-A_r \tag{4}$$

$$A_{\mathrm{p}}=R\times K\times L\times S \tag{5}$$

$$A_r=R\times K\times L\times S\times C\times P_s \tag{6}$$

where A_c refers to the amount of soil conserved (t/(ha·yr)); A_{p} refers to the potential soil erosion (t/(ha·yr)); A_r refers to the actual soil erosion (t/(ha·yr)); R refers to the erosion index by rainfall; K refers to the soil erosion factor; L refers to the slope length factor; S refers to the slope; C refers to the vegetation cover factor; P_s refers to the conservation practices factor, ranging from 0 to 1.

Water conservation. Water conservation in the TLB is an important part of ecological regulation services to provide protection for life and production. The function of water conservation is the integrated performance of water ecosystem and various ecological processes, such as forest, soil and wetland. Vegetation conserves water through the process of rainfall interception, evapotranspiration, sorption and storage (Li et al., 2006). In general, water conservation by vegetation can be calculated by summation of canopy retention, litter absorption, and soil storage (Su et al., 2012b).

$$Q_{\mathrm{t}}=Q_1+Q_2+Q_3 \tag{7}$$

$$Q_1=P\times\varepsilon\times A \tag{8}$$

$$Q_2=D\times r\times A \tag{9}$$

$$Q_3=\sum_{i=1}^{28}FMC\times h_i\times A \tag{10}$$

$$FMC=0.003075\times n_1+0.005886\times n_2+0.008039\times n_3+0.002208\times O_a-0.14340\times R \tag{11}$$

where Q_{t} refers to the total water retention capacity of the vegetation; Q_1 refers to the canopy interception of the vegetation; Q_2 refers to the water retention capacity of the litter; and Q_3 refers to the interception amount of the soil layer; P refers to the annual rainfall; ε refers to the canopy retention; D refers to the litter dry weight; r refers to the maximum water holding capacity; FMC refers to the maximum water holding capacity; h_i refers to the different kinds of soil thickness; n_1 refers to the topsoil sand fraction; n_2 refers to the topsoil silt fraction; n_3 refers to the topsoil clay fraction; O_a refers to the topsoil organic carbon; R refers to the topsoil reference bulk density. The values of ε, D, r were determined by the main vegetation type (Wen and Liu, 1995). Soil data in the TLB were derived from the Chinese Soil Data Set (v1.1).

Flood regulation. Floods put significant pressure on human security. The function of lakes and wetlands in the basin can effectively regulate flood and alleviate flood threat, which plays an important role in alleviating and preventing flood. Based on the relationship between water area for lakes and available storage capacity, lakes' regulation model was constructed (Rao et al., 2014). The flood storage of the wetlands can be calculated in the soil and surface (Wang et al., 2017).

$$C_l = \mathrm{e}^{4.924} \times A^{1.128} / 10^4 \tag{12}$$

$$C_s = S \times h_1 \times \rho \times (F - E) / \rho_w \times 0.01 + S \times h_2 \times 0.01 \tag{13}$$

where C_l refers to the available storage capacity of lakes; A refers to the water area of lakes; C_s refers to the available storage capacity of wetlands; h_1 refers to the depth of soil water storage in wetlands; F refers to the soil saturated water content in the wetlands; E refers to the natural water content before the inundation of wetlands; ρ refers to the soil bulk density of the wetlands; h_2 refers to the wetland surface backwater height; S refers to the area of wetlands.

2.2.3 Cultural service

Forest recreation. Forest recreation service refers to the entertainment and leisure functions for people by the forested areas. It was evaluated by the area of forest land cover in the TLB in 2010. The area ratio of the forest in each town was calculated as the forest recreation service (Raudsepp-Hearne et al., 2010).

2.3 Biodiversity maintenance service

Biodiversity maintenance is one of the most important functions of ecosystem in maintaining gene, species and ecosystem diversity. Biodiversity is affected by natural factors and human activities. Reference to the technical guidelines for the delineation of ecological protection red line (EPRL), quantitative indicators were used to assess biodiversity maintenance functions.

$$S_{\text{bio}} = NPP_{\text{mean}} \times F_{\text{pre}} \times F_{\text{tem}} \times (1 - F_{\text{alt}}) \tag{14}$$

where S_{bio} refers to the biodiversity maintenance services; NPP_{mean} refers to the average value of NPP for many years; F_{pre} refers to the annual precipitation data over many years and is normalized to 0–1; F_{tem} refers to the temperature parameter and is normalized to 0–1; F_{alt} refers to the elevation parameter and is normalized to 0–1.

2.4 Data source

The following five datasets were used to measure eight ecosystem services interactions and biodiversity maintenance service: a land cover dataset, a soil dataset, a meteorological dataset, a statistical dataset, and one other dataset (Table 1). The five datasets were described as belows.

(1) Land use dataset: Land use data of the TLB from Lake-Watershed Science Data Center, National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://lake.geodata.cn), which were derived from Landsat TM images, including urban area, cropland, forest, water and unutilized classes.

(2) Soil dataset: Soil data in the TLB were derived from the Chinese Soil Data Set (v1.1) of the Harmonized World Soil Database 1.1 (HWSD) constructed by the United Nations Food and Agriculture Organization (FAO) and the Vienna International Institute for Applied Systems (IIASA) (Fischer et al., 2008) (http://westdc.westgis.ac.cn). The data in China are the 1 : 1 000 000 soil data provided by the Second National Land Survey. The soil bulk density, soil thickness, sand, silt, clay and organic matter content are the main data.

(3) Meteorological dataset: The data of monthly rainfall, total solar radiation, monthly mean temperature and annual accumulated temperature of each meteorological station in the TLB are from China Meteorological Data Network (http://data.cma.cn).

(4) Statistical dataset: The data of crop production, aquatic product yield and water production coefficient were derived from Jiangsu Statistical Yearbook 2011 (JPBS, 2011), Zhejiang Statistical Yearbook 2011 (ZPBS, 2011), Shanghai Statistical Yearbook 2011 (SBS, 2011), Anhui Statistical Yearbook 2011 (APBS, 2011).

(5) Other datasets: Digital Elevation Model (DEM) data were acquired through the United States Geological Survey (USGS) (USGS, 2004). The Normalized Difference Vegetation Index (NDVI) data were acquired through the Moderate-Resolution Imaging Spectroradiometer (MODIS) Project (MOD13) of the Numerical Terra Dynamic Simulation Group (Zhao and Running, 2010).

The statistical dataset was used for crop production and aquatic production calculation. The soil dataset was mainly used for soil conservation and flood regulation. Meteorological datasets were used for three ecological models construction (NPP, freshwater supply, water conservation and biodiversity maintenance). Forest recreation service was derived from the land use dataset. All the geospatial data were resampled to the 1-km grid with Lambert Conformal Conic projection.

Table 1 Five datasets used to estimate eight ecosystem services

Data	Time	Scale/form/resolution	Source
Land cover	2010	Taihu Lake Basin, vector shapefile, 30 m	http://lake.geodata.cn.
Harmonized World Soil Database 1.1	2009	China, grid, 1 km	http://westdc.westgis.ac.cn.
Digital Elevation Model	2004	TLB, grid, 90 m	ftp://ftp.glcf.umiacs.umd.edu.
Meteorological factors	2010	TLB, grid, 1 km	http://data.cma.cn.
Normalized Difference Vegetation Index	2010	TLB, grid, 1 km	http://modis.gsfc.nasa.gov.
China Soil Database	2000	China, grid, 1 km	http://vdb3.soil.csdb.cn.
Statistical data	2011	Province, spreadsheet	http://www.jssb.gov.cn, http://www.zj.stats.gov.cn, http://www.stats-sh.gov.cn, http://www.ahtjj.gov.cn.

2.5 Data processing

ArcGIS 10.1 was used to spatial data processing. We computed summary statistics and cumulative frequency distributions (CFDs) of all the ecosystem services on the 1-km grid. We computed the Moran's I with the queen contiguity to test the spatial clustering. Then, we identified hotspots and coldspots of the services by the upper 20th and lowest 20th percentile (by area) of every service. We defined cells on the landscape that were within the upper 20th percentile were hot-spots, and those within the lowest 20th percentile were coldspots. Based on 1000 random sampling points across the basin, we used Pearson's correlation to assess the pairwise relations between ecosystem services. Then, Principal Component Analysis (PCA) was applied to quantify main multivariate interrelationships among the ecosystem service variables in assessing if ecosystem services co-occur in spatial ecosystem bundles. Following the Kaiser-Guttman criterion (eigenvalue > 1) (Plieninger et al., 2013), we extracted the significant factors and the factor loadings of the eight services on the sampling points. Combined with eight services, simulating the magnitude of trade-offs and synergies in the TLB. All statistical analyses were calculated in SPSS18.0.

3 Results and Analyses

3.1 Spatial patterns of ecosystem services

There were great differences among eight ecosystem services in the TLB (Table 2, Fig. 2) and they were spatially clumped (Moran's $I > 0.40$, $P < 0.01$). The clumped distribution of ecosystem services is in accordance with the distribution of geographical endowment. For example, higher crop production clumped in flat regions in the southeast and northwest, while higher forest areas gathered in mountainous regions. The low crop production areas are located in the hills of the southwestern and the economically developed areas such as Shanghai and Suzhou. Freshwater supply is gradually reduced from south to north in the TLB. High aquatic production is mainly distributed in the coastal and southeast part with intensive river networks. The high NPP areas are distributed in the southwestern woodland and agricultural land. NPP is low in construction lands. The distribution of soil conservation had a similar spatial pattern in the southwest of TLB. The high flood regulation areas are in the lakes and wetlands. Forest recreational service value decreases from southwest to northeast.

Table 2 Ecosystem services, indicator, median, and range for eight ecosystem services quantified in the Taihu Lake Basin in 2010

Ecosystem services	Service	Indicator	Estimated values in 2010
Provisioning services	Crop production	Annual crop output	198.31 (29.4–469 t/km^2)
	Freshwater supply	Annual water yield	0.59 (0.3–1.14 10^6 t/km^2)
	Aquatic production	Annual aquatic yield	36.52 (1.31–82.97 t/km^2)
Regulating services	NPP	Amount of carbon stored	126.88 (0–212.66 g C/m^2)
	Soil conservation	Amount of soil stored	3.23 (0–1156.89 100 t /km^2)
	Water conservation	Amount of water contained	21.41 (0–54.83 10^4 t/km^2)
	Flood regulation	Amount of water alleviated	0 (0–189.63 10^4 m^3)
Cultural service	Forest recreation	Amount of forest area percentage	11.12 (0–98%)

Note: NPP is net primary productivity

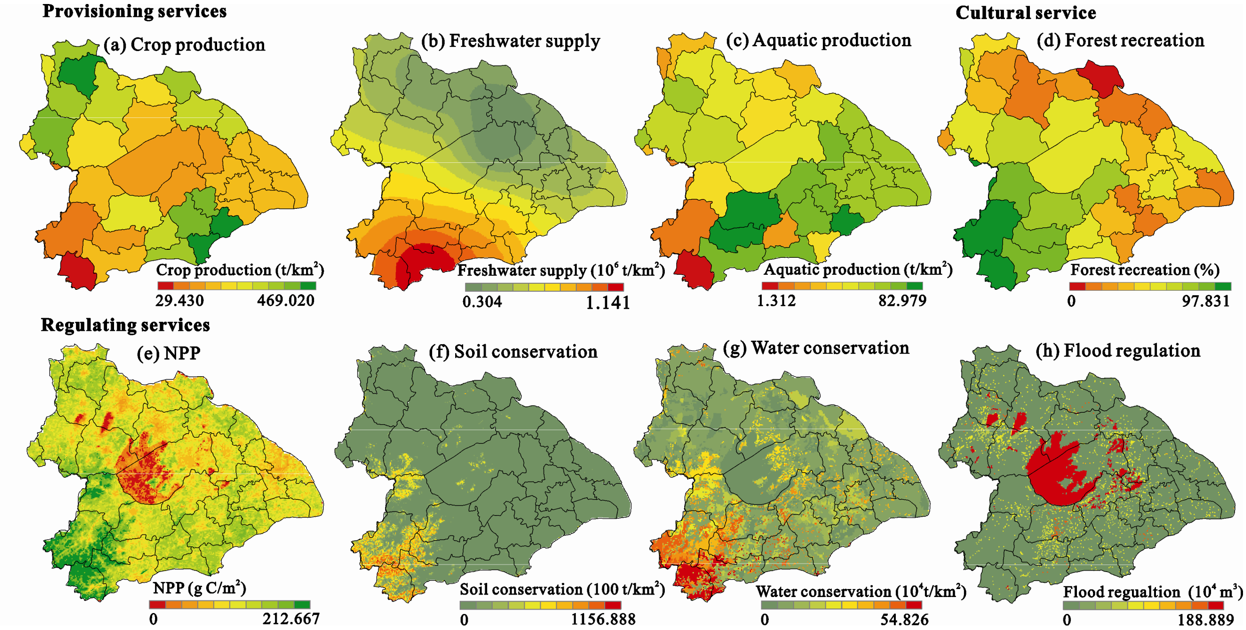

Fig. 2 Spatial distributions of eight ecosystem services in the Taihu Lake Basin in 2010. NPP is net primary productivity

The upper 20th and lowest 20th percentile (by area) of each service was used to define the ecosystem service hotspots and coldspots. The spatial distribution of services' hotspots and coldspots of eight ecosystem services were shown in Fig. 3. There were no eight services in the 20th of the strongest hotspots in the above region. And lack of eight services in the region under the 20th together in the TLB too. The hotspots of ecosystem services in the TLB were mainly located in the south, while the low values are in the east, middle and northwest. The coldspots were mainly located in the northern, and the low value area was widely distributed in the southeast and west of the basin.

3.2 Interactions of ecosystem services

There were 28 pair-wise correlations between ecosystem services (13 positive, 10 negative, 5 uncorrelated) in Table 3. Freshwater supply and forest recreation have the strongest positive correlation. NPP and flood regulation have a negative correlation. Forest recreation had high correlation with freshwater supply and regulating services (except for flood regulation). Aquatic production

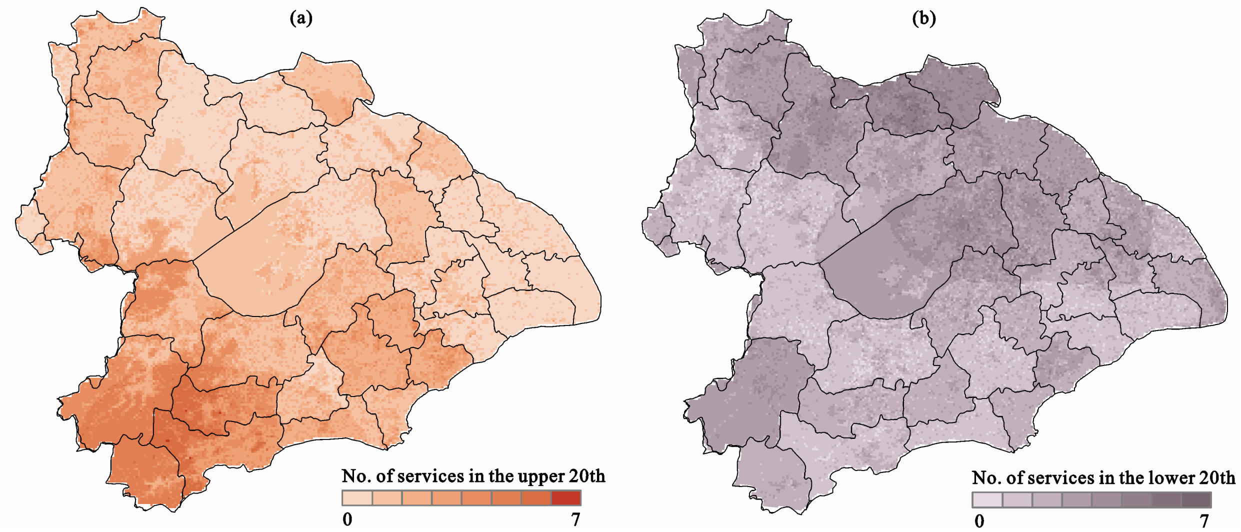

Fig. 3 Ecosystem services' spatial clustering distribution: (a) hotspots in the upper 20th percentile; (b) coldspots in the lowest 20th percentile. The darker color shows areas with higher values and lighter shows lower values.

Table 3 Pearson's correlations analysis of the pairwise interactions between ecosystem services were divided into positive, negative, and no correlations. High correlation 0.5–1.0 (dark gray), moderate correlation (medium gray) 0.3–0.5, weak correlation (light gray) 0.1–0.3, no correlation 0.0–0.1 (white)

Positive correlations		Negative correlations		Uncorrelated	
FS vs. FR	0.661**	NPP vs. WR	–0.573**	AP vs. NPP	0.037
SC vs. FR	0.567**	CP vs. FR	–0.563**	AP vs. WR	–0.011
NPP vs. WC	0.564**	WC vs. WR	–0.490**	AP vs. WC	–0.044
SC vs. WC	0.524**	CP vs. SC	–0.289**	WR vs. FR	–0.070*
WC vs. FR	0.417**	AP vs. FR	–0.257**	FS vs. WR	–0.090**
FS vs. SC	0.408**	CP vs. FS	–0.196**		
NPP vs. SC	0.400**	AP vs. SC	–0.186**		
FS vs. WC	0.351**	CP vs. WR	–0.173**		
FS vs. NPP	0.320**	SC vs. WR	–0.130**		
NPP vs. FR	0.276**	CP vs. WC	–0.129**		
FS vs. AP	0.161**				
CP vs. AP	0.130**				
CP vs. NPP	0.125**				

🟥 Provisioning services 🟩 Regulating services 🟦 Cultural service

Notes: CP: Crop production; FS: Freshwater supply; AP: Aquatic production; NPP: Net primary production; SC: Soil conservation; WC: Water conservation; WR: Flood regulation; FR: Forest recreation. **Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).

had lower correlation with other services. Provisioning services (except for freshwater supply) had primarily negative correlations or uncorrelation with forest recreation and regulating services. There were weak correlations among provisioning services. Freshwater supply had predominantly positive correlations with others services.

3.3 Bundles of ecosystem services

Based on the correlation coefficients, a principal component analysis (PCA) based factor analysis with a varimax rotation was used to find the bundles between the services. The first three factors accounted for 74.179% of the total variation in Table 4 (eigenvalue > 1). The first factor represents the trade-offs between crop production, freshwater supply, soil conservation and forest recreation and accounted for 31.149% of the total variation. The second factor accounted for additional 28.673% of the variation in the ecosystem services and represented the trade-offs of the NPP and water conservation and flood regulation. The third factor also represents a spatial synergy between freshwater supply and aquatic production and accounted for 14.357% of the variation. There was no service remained independent in the TLB.

Table 4 Loadings of ecosystem service indicators on principal component analysis (with varimax rotation), with the 1000 random points in the Taihu Lake Basin

Ecosystem service	Factor1	Factor2	Factor3
Crop production	**–0.728**	0.283	0.166
Freshwater supply	**0.703**	0.236	**0.465**
Aquatic production	–0.155	–0.021	**0.927**
NPP	0.145	**0.853**	0.100
Soil conservation	**0.662**	0.395	–0.158
Water conservation	0.383	**0.738**	–0.027
Flood regulation	0.141	**–0.836**	0.026
Forest recreation	**0.905**	0.176	–0.090
Variance explained%	31.149	28.673	14.357

Notes: Factor loadings ≥ 0.45 are shown in bold. NPP refers to the net primary production

The spatial patterns of trade-offs and synergies were intricate. The strongest trade-offs between crop production, freshwater supply, soil conservation, and forest recreation occurred in the southwestern (Fig. 4a). The secondary trade-offs between NPP and water conservation and flood regulation were mainly distributed in the southwest and western regions of the basin (Fig. 4b). Synergies of freshwater supply and aquatic production mainly occurred in the southeastern basin and coastal areas (Fig. 4c).

4 Discussion

4.1 Interaction among ecosystem services

The interactions between different ecosystem services

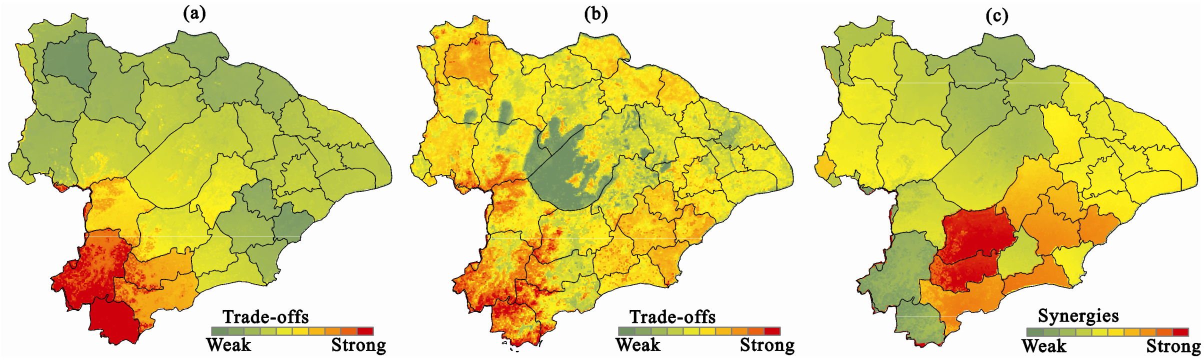

Fig. 4 Spatial patterns of the trade-offs and synergies: (a) Factor 1, trade-offs. Red represents where freshwater supply, soil conservation and forest recreation are high, and crop production is low. (b) Factor 2, trade-offs. Red represents locations where NPP and water conservation are high, whereas flood regulation is low. (c) Factor 3, synergies. Red represents locations where both freshwater supply and aquatic production are high.

are characterized by positive and negative relationships (Carpenter et al., 2009). In general, there is a positive relationship within the regulating services, indicating synergy or at least no conflicts. Agricultural services (crop, aquatic) show a negative correlation between regulating services and cultural services. These patterns indicates that agricultural lands may limit the availability of other ecosystem services lands (Vos and Meekes, 1999; Foley et al., 2005). Regulating services and cultural services are not very exclusive or easier to integrate (DeFries et al., 2004).

The latter fact is consistent with the findings of the Canadian study that a positive relationship is more likely to be formed among regulating services (Raudsepp-Hearne et al., 2010), while Danish's studies are cultural services (Turner et al., 2014). Regulating services and cultural services are easy to form synergies. Regulating services may be consistent in different spatial scales. Flood regulation service is mainly occurred in lakes and wetlands, so it has a different relationship on terrestrial ecosystem regulating services. Cultural services produced by forest for leisure and tourism do not take up too much land (Rounsevell et al., 2003).

There are highly positive relationships between forest recreation, freshwater supply, soil conservation and water conservation. Positive relationships among multiple services help maintain the basin landscape diversity. Forest recreation showed a highly negative relationship with crop production and aquatic production. It may be related to the aforementioned conflicts of the use of lands. Freshwater supply in the TLB is mainly from rainfall recharge. Abundant precipitation stimulates the growth of vegetation shrubs, as well as increasing carbon fixation and oxygen release capacity, which improved water conservation and forest cover to create a good natural recreation.

Many services have competition in land resources. The agricultural provision services (crop production, aquatic production) are negatively correlated with forest recreation and soil conservation, which is consistent with findings in Denmark. Agricultural provision services are produced by cultivated land and territorial waters, while forest recreation service mainly distributes in the forest-covered areas. There is a conflict in the demand of agricultural land and forest land. High population growth increased the demand of agricultural supply products in the TLB in recent years. Improving the per unit area of crop production and increasing cultivated land area could solve food problem. Meanwhile, a large number of farmland cultivation and aquaculture lands may threaten the soil conservation.

It is very interesting that freshwater supply have high correlation with other services. It has a highly positive correlation with regulating services (except for flood regulation) and cultural service (r > 0.32). Within the provisioning services, freshwater supply service is negatively correlated with crop production and positively correlated with the aquatic production. The research in Denmark suggested that drinking-water supply was not associated with any agricultural provisioning services. The similar research in Canadian suggests that there are positive correlations between different supply services. These works suggested that provisioning services are affected by geographical differences, under the influence of different meteorological factors, environmental factors, and social factors (population distribution pattern).

4.2 Trade-offs and synergies among ecosystem services

There were not only paired interactions among ecosystem services, but also bundles of multiple ecosystem services formed as spatial trade-offs and synergies (Turner et al., 2014). Many former researchers have found that there are trade-offs between provisioning services, regulating services and cultural services in different landscape scales (Turner et al., 2014; Yang et al., 2015). Our analysis showed that similar trade-offs occurred between provisioning services (crop production, freshwater supply) and regulating service (soil conservation) and cultural service (forest recreation). However, we found that increase of provisioning services did not always result in decrease of regulating services or cultural services, such as freshwater supply and soil conservation and forest recreation. Abundant freshwater supply will result in higher environmental benefits. The trade-offs between freshwater supply and crop production was consistent with other basin-scale studies (Qiu and Turner, 2013). Surprisingly, this study found that trade-offs among regulating services which is not consistent with the findings of relevant scholars (Raudsepp-Hearne et al., 2010; Qiu and Turner, 2013). Due to the different assessment object, multiple services may have the opposite results. We also found synergies between the provisioning services (freshwater supply and aquatic production) in the TLB, which was not reported in other studies. Due to the complex multi-scale effects of ecosystem services, agricultural provisioning services are mostly in small scales. Cultural services are more related to the provincial and municipal scales. We should pay attention to regulation services in the national scale (Fu et al., 2013). Compared with previous studies (Raudsepp-Hearne et al., 2010; Turner et al., 2014; Yang et al., 2015), some spatial relationships were found in multiple spatial scales.

Biodiversity influences ecosystem services formation and maintenance through ecosystem attributes and processes (Fan et al., 2016). The higher biodiversity, the broader the functional character of the ecosystem and the higher and more stable ecosystem services. The higher biodiversity maintenance service clumped in the southeast and southwest, while lower biodiversity maintenance service areas gathered in the north (Fig. 5). The trade-offs or synergies are the phenomena of spatiotemporal variation of biodiversity. There are two different relationships between the trade-offs and biodiversity (Fig. 6). Factor 1 (trade-offs) and biodiversity show the process of first increase and decrease, while the Factor 2 (trade-offs) and biodiversity show the trend of increasing or decreasing at the same time. Factor 3 (synergies) increases with the increase of biodiversity, but increases to a certain threshold, the synergies is basically unchanged. As a whole, ecosystem services include a variety of spatial interactions, and understanding the relationship between biodiversity and ecosystem services is the basis of ecosystem management.

4.3 Human activities and ecosystem services

There are sensitive and interactive between ecosystem services and human activities, which reflected in demand-action-pressure-state-response closed and chain-like (MA, 2005). Based on the human development index (HDI), human activities were assessed by the integrated human activity index (HAI) in the Yanhe River Watershed (Su et al., 2012a) and the Guanzhong-Tianshui economic region (Li and Zhou, 2016). Previous studies showed that there was a significant negative correlation between HAI and water conservation and soil conservation (Fig. 7). However, HAI was not associated with NPP and CSOP in Yanhe and Guanzhong economic regions. Irrational land use and vegetation degradation in the Loess Plateau are the main causes of ecological degradation (Fu and Gulinck, 1994). Rapid expansion of urban areas and population have severely threatened the ecological sustainability of the TLB (Xu et al., 2016). It is desirable to explore the relationship

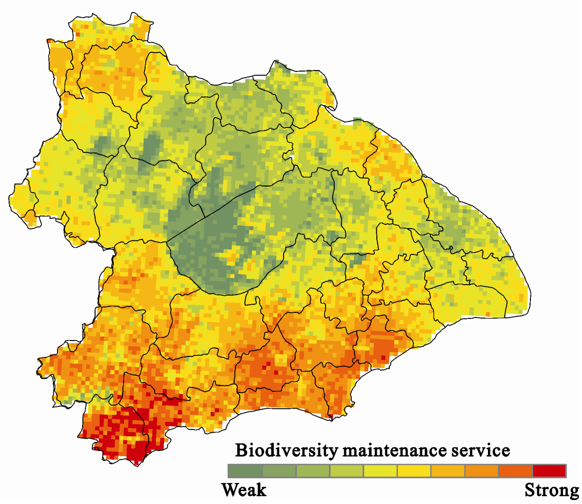

Fig. 5 Biodiversity maintenance service in the Taihu Lake Basin in 2010

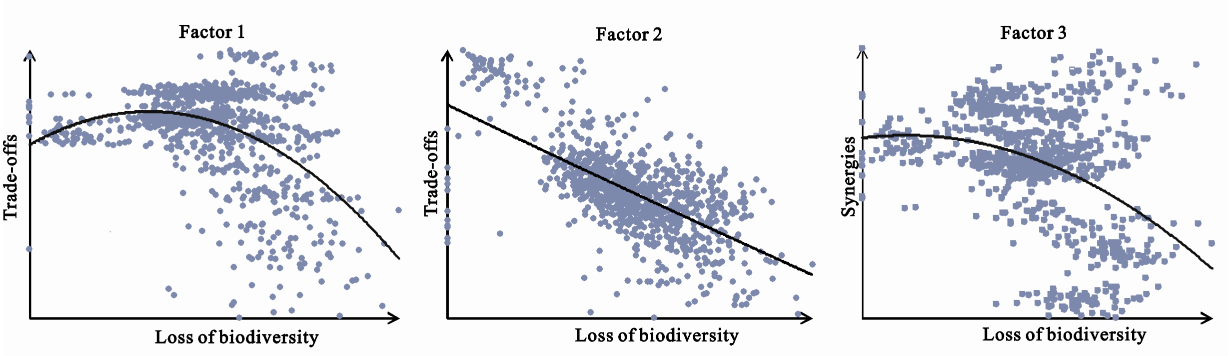

Fig. 6 Relationships between biodiversity and trade-offs or synergies, with the 1000 random points in the Taihu Lake Basin in 2010

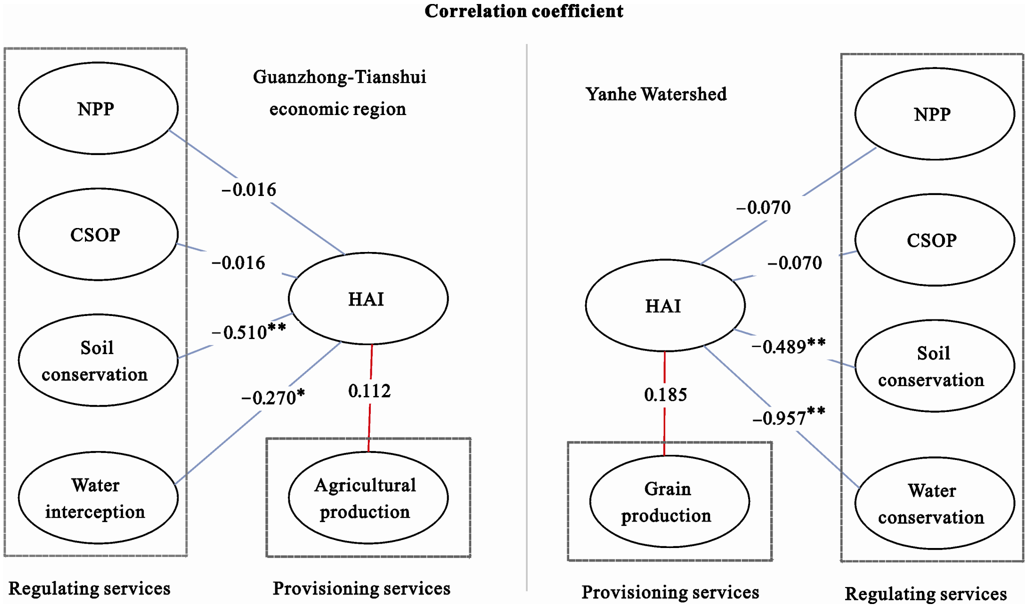

Fig. 7 Comparison of correlation on human activities and ecosystem services in different study. The correlation coefficient of Guanzhong-Tianshui economic region and Yanhe Watershed are referenced by Li and Zhou (2016) and Su et al. (2012a). Circles represent different ecosystem services or human activities. Blue lines indicate negative, red lines positive. Line width is scaled based on strength of correlation. Human Activity Index (HAI) was calculated by integrating the factors of human population, farmland ratio, road influence, and residential influence (Su et al., 2012a); NPP: Net primary production; CSOP: Carbon sequestration and oxygen production. **Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).

between human activities and ecosystem services in the TLB and the impact of human activities in further research.

5 Conclusions

Ecosystem services include a variety of spatial interactions, and understanding the relationship between biodiversity and ecosystem services is the basis of ecosystem management. There are trade-offs between provisioning services (crop production, freshwater supply) and regulating services and cultural service, while synergies exist in provisioning services. Trade-offs and synergies are the phenomena of spatiotemporal variation of biodiversity and their spatial patterns are intricate. The spatial relationships of multiple services are consistent and some spatial relationships were found in multiple spatial scales. The spatial distribution patterns of ecosystem services are similar with geographic resource endowment. The hotspots of ecosystem services were mainly located in the south, while the coldspots were mainly located in the north. The strongest trade-offs between crop production, freshwater supply, soil conservation, and forest recreation occurred in the southwestern region. The secondary trade-offs between NPP and water conservation and flood regulation were mainly distributed in the southwestern and western regions. The synergies of freshwater supply and aquatic production mainly occurred in the southeastern basin and coastal areas.

Due to the differences in geographical resource endowments, most of the landscape cannot provide a variety of high-services at the same place. Local government should optimize the allocation of resources to maximize the overall ecosystem service functions. In the southwest of the basin, there are high trade-offs between crop production and other services. With rapid population growth and urbanization, this region needs to increase the provisioning services at the expense of reduction of other services. It is critical to maintain the provisioning services, seek optimization of resources allocation, and improve the overall functions of ecological services. In the southeastern and coastal areas, there are high synergies between freshwater supply and aquatic production. Aquatic productivity is greatly influenced by water resources, which enable local residents to better access to aquatic products, increasing the supply of protein nutrition.

Our future research plans include: 1) to use more accurate models instead of social statistics to calculate the service values and verify the accuracy of the relevant models; 2) to analyze the temporal and spatial changes of the trade-offs and synergies in the TLB; 3) to explore the impact of human-induced and natural environmental changes on ecosystem services and their interactions in the TLB.

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