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# Temporal variation and spatial scale dependency of ecosystem service interactions: a case study on the central Loess Plateau of China

Ying Hou · Yihe Lü · Weiping Chen · Bojie Fu

## Abstract

*Contexts* An important feature of ecosystem service interaction is that it changes over time and across spatial scales.

*Objectives* This research aims to find which ecosystem service interactions temporally vary and depend on spatial scale.

*Methods* We calculated six ecosystem services of the Baota District on the central Loess Plateau of China for 2000, 2005, and 2010. Furthermore, we quantified the interactions among these services at the beginning and after the end of the first phase of the Grain for Green Program in this area, and across the pixel scale of 1 km$^2$ and the town scale.

*Results* Water yield decreased significantly, and habitat quality, net primary productivity, and evapotranspiration increased significantly across different land use types from 2000 to 2005. The synergy between food productivity and water yield, and the trade-off between water yield and evapotranspiration, greatly reduced from 2000 to 2010 at the pixel scale. Water yield was a trade-off to habitat quality, NPP, and recreation capacity in 2000 at the pixel scale while a synergy to the three services in 2010. The synergies between habitat quality and NPP, evapotranspiration, and recreation capacity at the pixel scale were enhanced from 2000 to 2010. Changes in the direction or significance of correlations among ecosystem services were observed across the pixel and town scales in 2000 and 2010.

*Conclusions* This study contributes to increasing the understanding of the temporal variation of ecosystem service interactions caused by regional ecological restoration programs, and the spatial scale dependency of the interactions.

**Keywords** Ecosystem service · Synergy · Trade-off · Grain for Green Program · Land use change · Correlation analysis

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## Introduction

One ecosystem service may interact with other services, either in the form of a synergy or a trade-off (Bennett et al. 2009; Qiu and Turner 2013). Ecosystem service synergy denotes a situation in which a pair of services are enhanced simultaneously; ecosystem service trade-off describes a situation in which the enhancement of one service causes the

reduction of another service (Bennett et al. 2009; Raudsepp-Hearne et al. 2010). Multiple ecosystem services must be considered simultaneously when managing human-environmental systems, as the human preference for one service may lead to loss of other services (Tallis et al. 2008; Bennett et al. 2009). An analysis of ecosystem service synergies and trade-offs can contribute to a comprehensive understanding of regional ecosystem service interactions, reveal inferior management options, and reinforce win–win management strategies that seek to meet the demands of different ecosystem service beneficiaries (Lester et al. 2013; Li et al. 2013).

Regulating ecosystem services are theoretically mostly exerted and mutually supporting in natural ecosystems, since they are, by nature, closely related to ecosystem structures, processes, and functions (Kandziora et al. 2013; Burkhard et al. 2014). The synergies among different regulating services are evidenced in many empirical studies (Raudsepp-Hearne et al. 2010; Haase et al. 2012; Jia et al. 2014; Xue et al. 2015). In addition, several investigations have reported positive relationships between regulating and cultural services, such as between carbon sequestration and forest recreation, and between local climate regulation and the recreation potential of close-to-home urban green spaces (Raudsepp-Hearne et al. 2010; Felipe-Lucia et al. 2014; Lauf et al. 2014; Yang et al. 2015). Although biodiversity is not an ecosystem service, it is closely connected with ecosystem processes and functions, and is a substantial prerequisite of ecosystem service supply (Haines-Young and Potschin 2010; Hou et al. 2014). Therefore, the relationship between biodiversity and ecosystem services is a particular focus. Relevant studies have identified synergies between biodiversity, regulating services, and cultural services (Egoh et al. 2009; Eigenbrod et al. 2010; Haase et al. 2012; Felipe-Lucia and Comín 2015). Meanwhile, net primary productivity (NPP) is a proxy of ecosystem process and function. Many studies have revealed a significant positive correlation between NPP and regulating services (Egoh et al. 2008; Kandziora et al. 2013; Jia et al. 2014).

An extensive body of literature has reported trade-offs between provisioning services and biodiversity, regulating, or cultural services (Raudsepp-Hearne et al. 2010; Martin-Lopez et al. 2012; Kandziora et al. 2013; Li et al. 2013). Reductions of

biodiversity, regulating, or cultural services are caused in large part by increases in crop or food production (Nelson et al. 2009; Raudsepp-Hearne et al. 2010; Yang et al. 2015). For example, noticeable trade-offs have been found in Europe between the potential for "habitat diversity" and "crop-based production" at the regional scale (Haines-Young et al. 2012), and between food production and recreational fisheries in the Great Barrier Reef World Heritage Area (Butler et al. 2013). Another example is in Quebec, Canada, where crop yield is negatively correlated with carbon sequestration, forest recreation, tourism, and deer hunting at the municipality spatial scale (Raudsepp-Hearne et al. 2010). Furthermore, food provision is significantly negatively correlated with local climate regulating services, and the recreation potential of close-to-home urban green spaces, under both growth and shrink scenarios in urban Berlin (Lauf et al. 2014).

Interactions among ecosystem services can shift over time (Tilman 2000; Jia et al. 2014; Li et al. 2015). In some cases, synergies or trade-offs are enhanced or weakened (Jia et al. 2014; Lauf et al. 2014; Zheng et al. 2014). For example, the synergies between NPP and evapotranspiration were enhanced from 2000 to 2008 in the core Grain for Green area in the middle of the Loess Plateau (Jia et al. 2014), and the trade-offs between water yield and crop production largely decreased from 2000 to 2008 in the Yanhe basin in China (Zheng et al. 2014). In other cases, correlations between pairs of ecosystem services disappear, or are even reversed in direction (e.g., changing from synergy to trade-off, see Jia et al. 2014). The temporal variations of ecosystem service interactions can be caused by natural factors or by anthropogenic reasons (Li et al. 2013; Jia et al. 2014; Zheng et al. 2014).

Aside from temporal variations, ecosystem service synergies and trade-offs can act differently at different spatial scales (van Jaarsveld et al. 2005; Felipe-Lucia et al. 2014). The changes in interaction involve both correlation significance and direction (positive to negative or vice versa, Anderson et al. 2009; Felipe-Lucia et al. 2014). One study in the floodplain of the Piedra River in central Spain has found food production to have no significant correlation with regulating services at the patch scale, with the correlation becoming significantly positive when upscaled to municipal and landscape scales (Felipe-Lucia et al. 2014). Another study reveals that correlation between ecological diversity and grassland productivity

changes with the variation in observation scales (Yue et al. 2005). The spatial scale dependency of ecosystem service interactions is embodied in the scale-dependent feature of the service provider and service beneficiary, and in the measurement and management of ecosystem services (van Jaarsveld et al. 2005; Zhang et al. 2013).

Scientists should be aware that ecosystem service interactions tend to change over time and across spatial scales. In addition, they should be cautious when providing suggestions to policy makers regarding the assessment and management of ecosystem services, to ensure that the effects of management actions on ecosystem service interactions remain consistent and are not reversed (Felipe-Lucia et al. 2014). However, only a small number of studies have investigated the temporal changes and spatial scale dependency of ecosystem service synergies and trade-offs thus far. This research deficiency limits our development of a comprehensive understanding of ecosystem service interactions and prevents consideration of this issue in ecosystem service management. We thus chose to focus on this issue and conducted a case study in the Baota District, a priority region of the Grain for Green Program on the central Loess Plateau of China. The specific objectives of this study were (1) to quantify the major ecosystem services of different land use types in the Baota District, (2) to reveal the temporal variations of ecosystem service interactions in the process of the implementation of the regional Grain for Green Program, and (3) to demonstrate the way in which ecosystem service interactions in the Baota District depend on spatial scale. Our work can extend the understanding of the temporal variation of ecosystem service interactions caused by regional ecological restoration programs, and the spatial scale dependency of ecosystem service interactions.

## Study area and methods

### Study area

The Baota District is part of the Yan'an Prefecture, and is located in the north of the Shaanxi Province on the central Loess Plateau of China ($36°10'36''$–$37°02'05''$N, $109°14'10''$–$110°05'43''$E, Fig. 1). It covers approximately 3500 km$^2$ and consists of 19 towns with 462,389 inhabitants (63% from rural areas

in 2011). This area has a semi-arid to semi-humid temperate continental climate with an average annual precipitation and temperature of approximately 500 mm and 9.6 °C, respectively (Statistics Bureau of Yan'an 2011). Its rugged landform is composed of steep hills, gullies, and loess soil susceptible to water erosion. Consequently, soil and water conservation, re-vegetation, and engineering measures have been implemented in this area since the early 1950s (Lü et al. 2015).

The Grain for Green Program (GGP) is the largest ecological restoration program in China. It relied on a public payment scheme and directly engaged 0.12 billion farmers in retiring and re-vegetating 92.7 thousand km$^2$ of sloping farmland in China between 1999 and 2008 (Lü et al. 2012). The Baota District was selected as one of the pilot regions and as a priority region of the first phase of the GGP by the central government in 1999. Approximately 400 km$^2$ of farmland, accounting for 11.4% of the total area, was converted to woodland over the following 8 years. The program involved all 19 towns of the district and 195,000 members of the rural population, an amount that accounted for 93.9% of the district's total rural population (Bai et al. 2009). The Baota District thus became one of the regions with the most effective vegetation restoration between 2000 and 2010 (Liu and Gong 2012).

### Land use classification

We used the remote sensing data of Landsat TM for the years 2000, 2005, and 2010 from the Geospatial Data Cloud website (http://www.gscloud.cn/) for the land use classification in this study. Images with a resolution of 30 m were acquired between July and August, when the spectral reflectance of vegetation indicates the peak of greenness. The object-oriented classification based on a decision tree was achieved using eCognition software. We then carried out manual correction and validation to ensure classification accuracy (Wang et al. 2014). The land uses were thus classified into eight categories, including woodland, grassland, farmland, residential areas, industrial and transportation land use, mines, waterbody, and barren areas. The accuracy of the land use maps was over 94%, and the Kappa indices were above 0.88 for all 3 years (2000, 2005, and 2010). Thereafter, we converted the raster land use data to shapefiles in ArcGIS
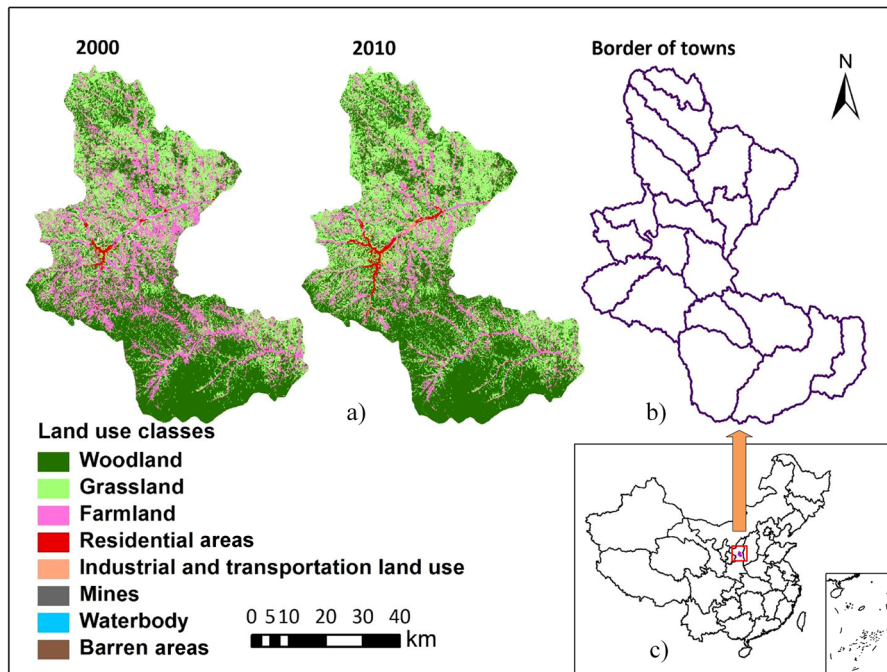
**Fig. 1** **a** Land use classes of the Baota District in 2000 and 2010; **b** border of towns in the Baota District; **c** location of the Baota District in China

10.0, and calculated the area of each land use class in the attribute table of the shapefiles for the 3 years. Finally, a table was made showing the areas of each land use class for the 3 years.

Ecosystem services quantification and mapping

We quantified and mapped six ecosystem services for each of the 3 years. The six ecosystem services were food productivity, water yield, habitat quality, NPP, evapotranspiration, and recreation capacity. The services were selected based on their significance for the Baota District and the availability of data to determine services. We quantified ecosystem services using different methods and data as specified in the following paragraphs. Ecosystem service values were mapped using ArcGIS 10.0 (the maps of the services are provided in Supplementary material-3). In addition, we calculated the mean values of food productivity for farmland and the other five services for woodland, grassland, farmland, and residential areas for each of the 3 years, so that the ecosystem services provided by different land use classes in different years can be compared. Industrial and transportation land use, mines, waterbody, and barren areas were not

considered, as several of the services were not applicable to these land use classes, and their areas were negligible compared to the other four land use types.

*Food productivity*

This measure indicates the food crop output per pixel in the unit of $10^3$ t/pixel (Qiu and Turner 2013). Food yield data for the 19 towns of the Baota District in 2000, 2005, and 2010 were used. The main food crops included wheat, maize, millet, beans, and tubers. We calculated this service for 3 years in three steps using ArcGIS 10.0. First, we overlaid a grid map of the research area with 1 km × 1 km square polygons and the farmland polygon map, and generated the farmland area value in each 1 km² polygon (Raudsepp-Hearne et al. 2010). Second, we linked data on food yield per cultivated land area for the 19 towns to a polygon map of these towns. Lastly, we converted the two polygon maps produced in the first two steps to raster maps and multiplied the two raster maps to produce a map with each pixel (1 km × 1 km) having the value of food crop output.

*Water yield and evapotranspiration (ET)*

Water yield was estimated in the unit of mm as the difference between precipitation and ET. This simplification is based on the assumption that annual water storage change is negligible in the Loess Plateau region (Lü et al. 2012; Jia et al. 2014). The precipitation data for 2000 and 2005, with a spatial resolution of 0.5 degrees, were derived from the Consortium for Spatial Information and interpolated to 1 km using the ordinary Kriging interpolation method in ArcGIS 10.0. The precipitation data for 2010 with a spatial resolution of 0.25 degrees were obtained from the China Meteorological Data Sharing Service System and interpolated to 1 km using the same method. ET data (mm) with a spatial resolution of 1 km were provided by the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences using the ETWatch model to estimate ET value (Wu et al. 2011). The maps of the ET values for every 10 days were summed to annual ET maps for 2000, 2005, and 2010. The calculation of water yield was implemented and the maps of this service with a resolution of 1 km were generated using ArcGIS 10.0.

*Habitat quality*

Habitat quality can serve as a proxy of biodiversity, as it relates to the capacity of the ecosystem to provide conditions suitable for individual and population persistence (Tallis et al. 2013). We used the InVEST habitat quality model to estimate the habitat quality (unitless relative value of 0-1) of our study area. The model integrates information on land use and threats to biodiversity to produce habitat quality maps (Tallis et al. 2013). It provides sample data including biophysical tables of habitats and threats. The biophysical table of habitats contains information on whether or not the land use types are considered habitats, and the sensitivity of habitats to each threat. The biophysical table of threats provides information on the threats' relative importance, or weight, and its impact across space. Habitats in this study were categorized into woodland, grassland, farmland, residential areas, and waterbody. Threats included farmland, residential areas, industrial and transportation land use, mines, road, and railway areas. The biophysical tables of habitats and threats in this study were adapted from Burkhard et al. (2009) and Hou

et al. (2015, 2016), and sample data from the InVEST habitat quality model. Essential changes were made to values in the biophysical tables based on the land use classification of the research area. Land use raster maps of the Baota District for 2000, 2005, and 2010 were used in the modeling, and the raster files of threats were created based on the land use, road, and railway network maps of the research area. The produced habitat quality maps have a resolution of 30 m and the pixels on a map with greater values indicate higher habitat quality compared with the rest of the map.

*Net primary production (NPP)*

NPP can be a proxy of global climate regulation service, as it represents the net carbon uptake from the atmosphere into biosphere (Ingraham and Foster 2008). It is closely related to carbon sequestration and is widely used to evaluate the patterns, processes, and dynamics of carbon cycling in ecosystems and to monitor environmental changes (Melillo et al. 1993; Zhao and Zhou 2005). NPP was quantified in the unit of $gC/m^2$ using the Carnegie–Ames–Stanford Approach (CASA) model in this study (Potter et al. 1993; Yuan et al. 2006). ArcGIS 10.0 was used to generate the maps of NPP with the pixel size of 250 m × 250 m. The details of the calculation is provided in Supplementary Material-1.

*Recreation capacity*

Recreation is a typical cultural ecosystem service. It is influenced not only by ecosystem and landscape properties but also by economic conditions and social cultures (Villamagna et al. 2013). Recreation capacity can be defined as the potential of ecosystems, landscapes, or regions to provide recreational services to humans. It differs from the actual recreation service, and is mainly determined by the geographical and biophysical properties of ecosystems or landscapes, such as land use type, vegetation type variety, and mountainous terrain (Haines-Young et al. 2012; Schröter et al. 2014). In this study, we incorporated land use type, slope, vegetation coverage, and landscape diversity in formulating the equation to calculate recreation capacity (unitless relative value of 0–1). The formulation of the equation was based on findings in extant literature, and the fact that rugged landform

and low vegetation coverage are two important environmental features of the study area. Consequently, the land use types having greater potential in providing recreation service, smaller slopes, greater vegetation coverage, and higher landscape diversity are more suitable for locals' recreational activities. The maps of recreation capacity with the pixel size of 30 m × 30 m were produced using ArcGIS 10.0. The calculation of recreation capacity is detailed in Supplementary Material-1.

Statistical analyses

We tested the differences in the mean values of water yield, habitat quality, NPP, evapotranspiration, and recreation capacity among different land use classes for 2010 using Games-Howell test, and the differences in the values of these five services provided by different land use classes among 2000, 2005, and 2010 using the Mann–Whitney $U$ test. These two test methods were used, since the variances were not homogenous. The ecosystem service raster maps of water yield, habitat quality, NPP, evapotranspiration, and recreation capacity were extracted by the shapefiles of different land use classes for 2000, 2005, and 2010, and the extracted maps were further converted to ASCII format data to derive the sample values for statistical analysis. The differences in the food productivity mean values of farmland among 2000, 2005, and 2010 were tested by means of multiple comparison using the Least Significance Difference Method following a one-way ANOVA.

In order to demonstrate ecosystem service interactions, we created scatter plots of the pixel values of pairs of ecosystem services for 2000 and 2010. A pixel scale of 1 km was selected to quantify ecosystem services interactions because it is the coarsest resolution of the raster maps of the six services. The pixel sizes of the maps of habitat quality, NPP, and recreation capacity were converted to 1 km$^2$ using the "Resample" tool in ArcGIS 10.0 in order to be consistent with the pixel sizes of the maps of the other three services. In addition, the Spearman correlation coefficients between pairs of ecosystem services were calculated and the bar plots presenting coefficient values were created for the 2 years. The scatter plots and correlation coefficients explicitly show the quantitative interactions among the six ecosystem services. Moreover, the differences in ecosystem service interactions between 2000 and 2010 can be revealed by comparing the scatter plots and correlation coefficients for the 2 years. Pairs of ecosystem services with $|r| \geq 0.5$ indicate high correlations, those with $0.3 \leq |r| < 0.5$ have moderate correlations and those with $|r| < 0.3$ demonstrate weak correlations. Positive correlations with a higher significance level and more concentrated data points indicate a more significant synergy between pairs of ecosystem services. In contrast, more significant negative correlations with more concentrated data points reveal more significant ecosystem service trade-offs. This study focuses on the landscape mosaics of the entire Baota District in the investigation of the ecosystem service interactions at the pixel scale. Therefore, we did not differentiate land use types when creating scatter plots and calculating correlation coefficients, although the ecosystem service interactions can differ across land use types (Felipe-Lucia et al. 2014; Jia et al. 2014).

Furthermore, we calculated the pixel mean values for the six ecosystem services of the 19 towns for 2000 and 2010 using the "Zonal Statistics as Table" tool in ArcGIS 10.0, and then created scatter plots and computed Spearman correlation coefficients between pairs of ecosystem services on the town scale. The scatter plots and correlation coefficients were grouped with those of the ecosystem service values at the pixel scale for the 2 years. Thereafter, the ecosystem service interactions were compared at the pixel scale and the town scale. All statistical analyses were performed using SPSS 17.0.

## Results

Land use changes in the Baota District

The major land use classes of the Baota District were woodland, grassland, and farmland, which accounted for 42.2, 29.7, and 27.2% of the total area in 2000, respectively (Table 1). The area of woodland and grassland increased by 7.5 and 22.05% from 2000 to 2005, respectively. In contrast, farmland area sharply decreased by 37.41% during this period. The rapid changes in the area of these three land use classes did not continue after 2005, and small area changes were observed from 2005 to 2010. In contrast, the area of artificial surfaces (including residential areas, industrial and transportation land use, and mines) continued

**Table 1** Areas of different land use classes (km²) of the Baota District in 2000, 2005, and 2010

| Land use classes | 2000 | 2005 | 2010 |
|---|---|---|---|
| Woodland | 1492.94 | 1604.61 | 1605.11 |
| Grassland | 1048.63 | 1279.88 | 1281.76 |
| Farmland | 961.55 | 601.85 | 587.94 |
| Residential areas | 23.67 | 38.6 | 45.17 |
| Industrial and transportation land use | 3.02 | 4.93 | 9.15 |
| Mines | 3.61 | 3.93 | 4.04 |
| Waterbody | 2.91 | 2.74 | 3.26 |
| Barren areas | 0.31 | 0.1 | 0.21 |

to grow rapidly over the course of the 10 years. Consequently, the area of artificial surfaces doubled from 2000 to 2010.

Ecosystem services of different land use classes

The average food productivity of farmland in the Baota District was 3.18, 3.05, and 3.53 t/ha in 2000, 2005, and 2010, respectively (Fig. 2). However, the one-way ANOVA and multiple comparison results did not show significant differences in the mean values of this service among the 3 years (Table 2, Table S2 in Supplementary Material-2).

The average water yield from residential areas was higher than that from woodland, grassland, and farmland in each of the 3 years (Fig. 2). This phenomenon was caused by the reason that residential areas generally had lower ET than the other land use types due to relatively low vegetation coverage, resulting in less water loss to the atmosphere from precipitation. Woodland generated the least water yield among the four land use classes in 2000 and 2005, and grassland had the smallest water yield mean value in 2010. The Games-Howell test results show that the mean values of water yield were significantly different at the 0.001 level among the four land use classes except between woodland and farmland, and between grassland and farmland in 2010 (Table S3 in Supplementary Material-2). The results of the Mann–Whitney $U$ test indicate that the mean values of water yield provided by the four land use classes were all significantly different among 2000, 2005, and 2010 in the Baota District ($p < 0.001$, Table 2).

Woodland had the best habitat quality in all the 3 years, followed by grassland and residential areas. In comparison, the habitat quality value of farmland was far lower than the other three land use classes (Fig. 2). The mean values of habitat quality were significantly different among the four land use classes in 2010 ($p < 0.001$, see Table S3 in Supplementary Material-2). The habitat quality of all the four land use classes increased significantly from 2000 to 2005 ($p < 0.001$) in varying degrees and remained nearly the same between 2005 and 2010 (Table 2).

With respect to NPP, woodland also displayed the greatest values in each of the 3 years, followed by grassland and farmland, whose NPP values remained close to each other over the 3 years. Residential areas generated the least NPP among the four land use classes in each of the 3 years (Fig. 2). The mean values of NPP were significantly different among the four land use classes in 2010 ($p < 0.001$, see Table S3 in Supplementary Material-2). The NPP of the four land use classes increased significantly from 2000 to 2005 ($p < 0.001$) and continued growing significantly ($p < 0.001$) in different degrees from 2005 to 2010 except for woodland (Table 2).

Evapotranspiration (ET) was generally highest in woodland-covered areas, second highest in the areas covered by farmland, followed by grassland and residential areas (Fig. 2). The differences in the mean values of ET were significant ($p < 0.05$) among the four land use classes except between grassland and farmland in 2010 (Table S3 in Supplementary Material-2). ET of the four land use classes experienced significant increases from 2000 to 2005 ($p < 0.01$) and declined in different degrees from 2005 to 2010 (Table 2).

With regard to recreation capacity in the 3 years, woodland had the highest values, followed by residential areas and grassland. In comparison, farmland's values were far lower than the other three land use
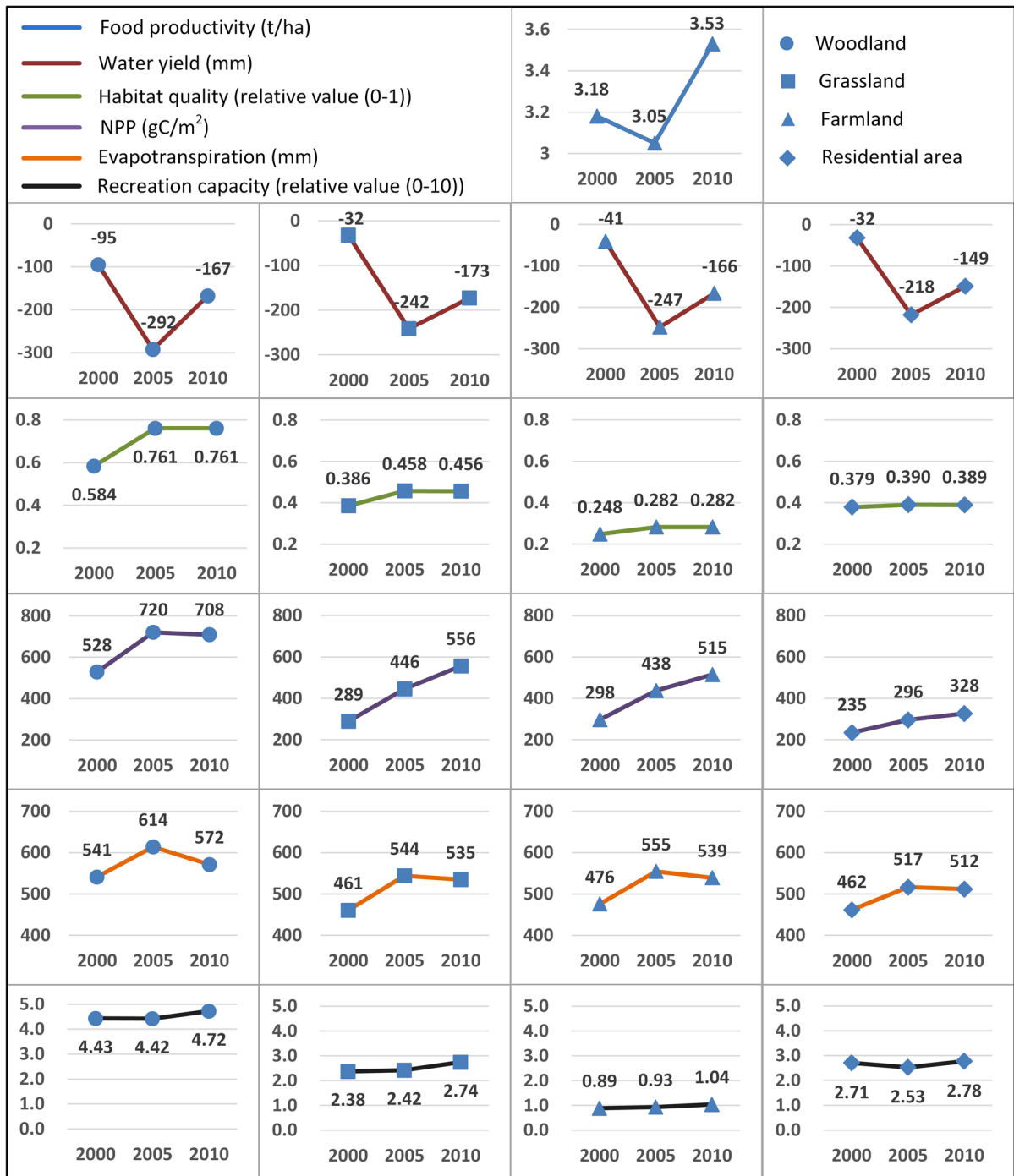
Fig. 2 Ecosystem service mean values of different land use classes of the Baota District in 2000, 2005, and 2010. Industrial and transportation land use, mines, waterbody, and barren areas were not considered as several of the services were not applicable to these land use classes and their areas were insignificant in comparison with the other four land use types

classes (Fig. 2). The mean values of recreation capacity were significantly different (p < 0.001) among the four land use classes in 2010 (Table S3 in Supplementary Material-2). This service increased significantly (p < 0.001) from 2000 to 2010 to different extents for all four land use classes (Table 2).

**Table 2** Differences of ecosystem service mean values of different land use classes in the Baota District among 2000, 2005, and 2010 and significance test results of the mean value differences

| Ecosystem service category | Ecosystem service type | Units | Woodland | | | Grassland | | |
|---|---|---|---|---|---|---|---|---|
| | | | 2000–2005 | 2005–2010 | 2000–2010 | 2000–2005 | 2005–2010 | 2000–2010 |
| Provisioning service | Food productivity[#] | t/ha | – | – | – | – | – | – |
| | Water yield[##] | mm | −197*** | 125*** | −72*** | −210*** | 69*** | −141*** |
| Habitat service | Habitat quality | relative value (0–1) | 0.177*** | 0 | 0.177*** | 0.072*** | −0.002 | 0.07*** |
| Regulating service | NPP | gC/m$^2$ | 192*** | −12*** | 180*** | 157*** | 110*** | 267*** |
| | Evapotranspiration | mm | 73*** | −42*** | 31*** | 83*** | −9* | 74*** |
| Cultural service | Recreation capacity | relative value (0–10) | −0.01** | 0.3*** | 0.29*** | 0.04*** | 0.32*** | 0.36*** |

| Ecosystem service category | Farmland | | | Residential areas | | |
|---|---|---|---|---|---|---|
| | 2000–2005 | 2005–2010 | 2000–2010 | 2000–2005 | 2005–2010 | 2000–2010 |
| Provisioning service | −0.13 | 0.48 | 0.35 | – | – | – |
| | −206*** | 81*** | −125*** | −186*** | 69*** | −117*** |
| Habitat service | 0.034*** | 0 | 0.034*** | 0.011*** | −0.001*** | 0.01*** |
| Regulating service | 140*** | 77*** | 217*** | 61*** | 32*** | 93*** |
| | 79*** | −16*** | 63*** | 55** | −5 | 50*** |
| Cultural service | 0.04*** | 0.11*** | 0.15*** | −0.18*** | 0.25*** | 0.07*** |

The significant difference of the mean values of food productivity of farmland among different years was tested using Least-Significance-Difference Method. The significant difference of the mean values of the other five services among different years was tested using the Mann–Whitney $U$ test. The significance tests were implemented using SPSS 17.0. Industrial and transportation land use, mines, waterbody and barren areas were not considered, as several of the services were not applicable to these land use classes and their areas were insignificant in comparison with the other four land use types

[#] Food productivity is only applicable for farmland. The mean values of this service were calculated by averaging the food productivity values of farmland of different towns. The unit of the value of this service is different from that at the pixel scale due to a distinct calculation method

[##] A negative value for water yield denotes annual evapotranspiration exceeds annual precipitation

* Means $p < 0.05$

** Means $p < 0.01$

*** Means $p < 0.001$

No * means $p \geq 0.05$

**Temporal variations in ecosystem service interactions**

The six ecosystem services investigated in this study displayed considerable interactions at the pixel scale. In addition, these interactions changed in different degrees from 2000 and 2010 (Fig. 3). Food productivity demonstrated a significant positive correlation with water yield in 2000, indicating a synergy between the two services. However, this significant correlation is not observed in 2010. On the contrary, this service was significantly negatively correlated with habitat quality, NPP, ET, and recreation capacity in both 2000 and 2010. These findings demonstrated noticeable trade-offs between food productivity and these four services. Water yield served as a trade-off to habitat quality, NPP, ET, and recreation capacity in 2000, since it was significantly negatively correlated with the other four services. Nevertheless, these trade-offs changed in 2010. For habitat quality and NPP, their correlations with water yield became significantly positive, indicating that their trade-offs to water yield had changed to synergies. As for recreation capacity, its correlation with water yield also became positive,
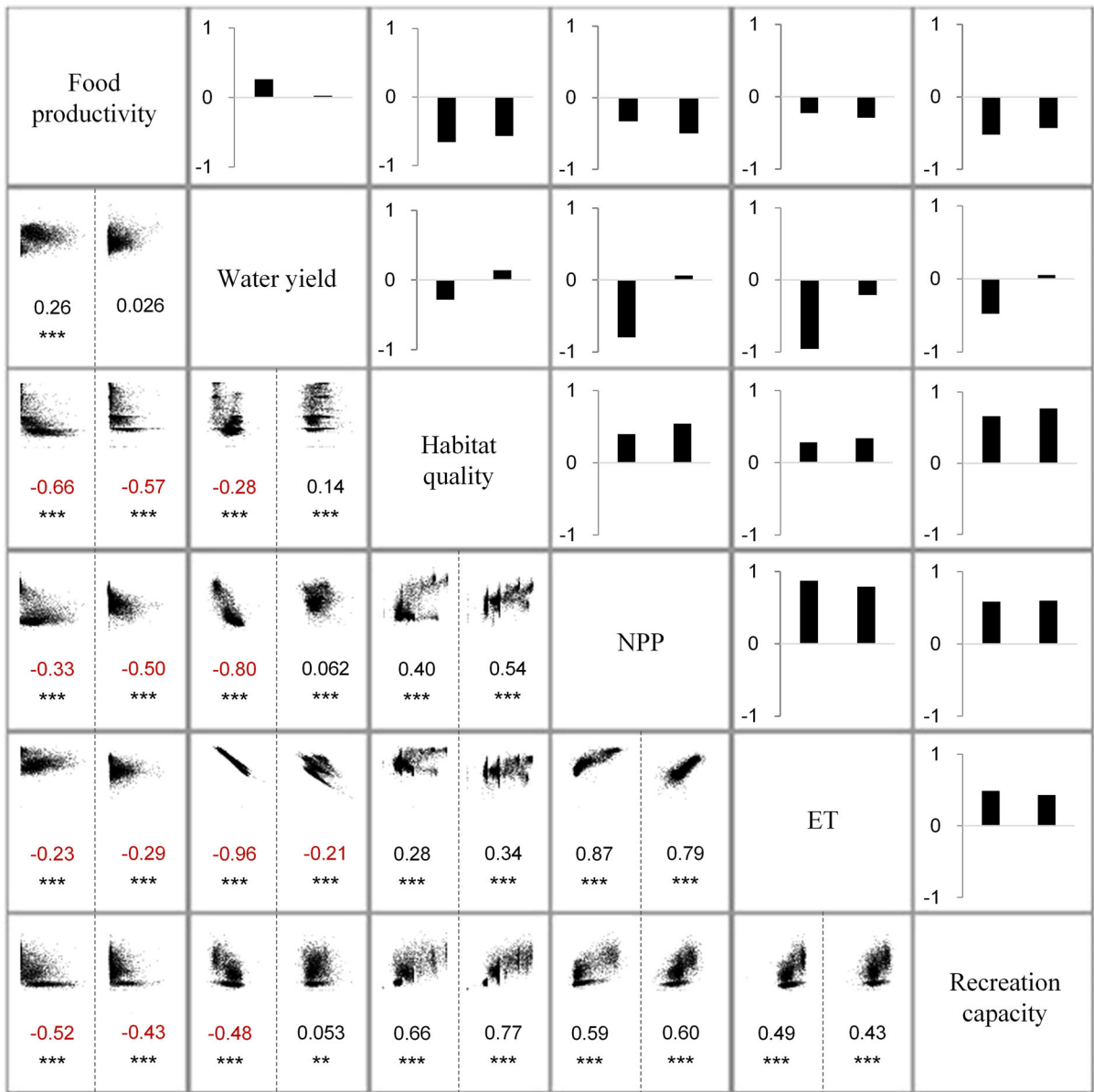
**Fig. 3** Correlations between pairs of ecosystem services and data points for the Baota District for 2000 and 2010 (Spearman correlation, *p < 0.05; **p < 0.01; ***p < 0.001, 3270 1 km²-sized pixels). *Bar charts* in the *top right half* of the figure present Spearman correlation coefficients which are in correspondence with the coefficient values in the *bottom left half*. The *columns* and *bars* on the *left side of grids* indicate 2000 and those on the *right side of grids* indicate 2010

with the significance level changing from p < 0.001 to p < 0.01. Furthermore, the correlation between ET and water yield remained negative but became much weaker, with the coefficient decreasing from −0.96 to −0.21.

Habitat quality showed significant synergies with NPP, ET, and recreation capacity, and these positive

relationships were enhanced from 2000 to 2010. NPP displayed significant synergies with ET and recreation capacity, and these close relationships remained consistent between 2000 and 2010. As for the interaction between ET and recreation capacity, notable synergy was observed both in 2000 and 2010.

**Fig. 4** Correlations between pairs of ecosystem services and data points for the Baota District at the pixel scale (*left columns*) and town scales (*right columns*) for 2000 (*bottom left half* of the figure) and 2010 (*top right half* of the figure). The numbers indicate Spearman correlation coefficient (*p < 0.05; **p < 0.01; ***p < 0.001, 3270 1 km²-sized pixels and 19 towns). The pixel scale and the town scale are not comparable in terms of correlation coefficients, since the sample sizes are not the same

### Ecosystem service interactions at different spatial scales

The interactions between several pairs of ecosystem services were inconsistent between the pixel scale and the town scale in 2000 (Fig. 4, left bottom half). For some pairs of ecosystem services, the direction of the correlations changed across the two spatial scales. This type of change referred to the correlations between food productivity and water yield, food productivity and NPP, and between food productivity and ET. As for the other inconsistent interactions of pairs of ecosystem service, the significance of interactions differed at different spatial scales. With

respect to trade-offs, water yield was negatively correlated with habitat quality at a p < 0.001 significance level at the pixel scale. However, the significance of the correlation no longer existed at the town scale. With regard to synergies, habitat quality was significantly positively correlated with NPP, ET, and recreation capacity at the pixel scale (p < 0.001), but this significance was considerably reduced at the town scale.

Compared to 2000, changes in the direction or significance of the correlations between more pairs of ecosystem services are observed across the pixel and town scales in 2010 (Fig. 4, top right half). The changes of correlation direction referred to the correlations between food productivity and water yield, between food productivity and ET, and between water yield and ET. As for the changes of the significance of ecosystem service trade-offs, food productivity was negatively correlated with habitat quality, NPP, and recreation capacity at a p < 0.001 significance level at the pixel scale. However, the significance levels were far lower at the town scale. With regard to the inconsistence of the significance of ecosystem service synergies, water yield was significantly positively correlated with habitat quality, NPP, and recreation capacity at the pixel scale, but this significance was considerably reduced at the town scale. Significance reductions in synergies are also observed between habitat quality and NPP, habitat quality and ET, as well as between ET and recreation capacity.

## Discussion

Our study found significant trade-offs between the food provision service (food productivity in this study) and habitat, regulating, and cultural services (habitat quality, NPP, ET, and recreation capacity in this study) at the pixel scale. This finding agrees with many published findings (Raudsepp-Hearne et al. 2010; Martin-Lopez et al. 2012; Lauf et al. 2014; Yang et al. 2015). As land use types rival with one another at the pixel scale in particular, an increase in farmland will probably reduce other vegetation covers (e.g., woodland or grassland). Consequently, those services supplied especially by farmland (e.g., food provisioning, see Fig. 2) are enhanced, whereas, regulating, habitat, and cultural services, which are largely provided by other vegetation covers at the pixel scale,

are reduced. For example, the sloping farmland on China's Loess Plateau, where this study' research area is located, caused serious soil erosion and water loss and greatly reduced carbon sequestration before the implementation of the Grain for Green Program (GGP) (Lü et al. 2012; Zheng et al. 2014). In addition to the rivalry between land use types at the pixel scale, the aggregation of the influences from different land use types on ecosystem services contributed to the trade-offs between food productivity and the two regulating services. Although farmland had high food productivity and moderate NPP and ET in the Baota District, trade-offs between food productivity and the two regulating services emerged when the influence from farmland was aggregated with that from forest and grassland at the pixel scale, because these two land use types had high NPP and ET but did not produce food (see Fig. 2). Water yield, the other provisioning service examined in this study, interacted with others services differently in different years at the pixel scale (Fig. 3). Jia et al. (2014), who investigated a larger area that was also located on the Loess Plateau, noted a similar phenomenon. In the study conducted by Jia et al. (2014), water yield was significantly positively correlated with NPP in 2000, but significantly negatively correlated with NPP in 2008. Interestingly enough, our results were opposite to these, as water yield served as a trade-off to NPP in 2000, but as a synergy to NPP in 2010. We attribute the most probable reasons for this phenomenon and for the inconsistency between our results and those of Jia et al. (2014) to the change in precipitation and the downscaling of precipitation data via interpolation. Precipitation is a deciding variable in calculating water yield in both our study and that conducted by Jia et al. (2014). The change in the spatial distribution of precipitation from one year to another substantially influences the spatial variation in water yield. As the precipitation raster maps in this study were generated by interpolating data from a larger resolution to a much smaller one, the maps produced rely heavily on the quality and quantity of the original precipitation data and the interpolation method. It is thus important for researchers to be aware of the uncertainties caused by data downscaling and upscaling, as using data from different spatial scales is often inevitable in ecosystem services studies (Wu et al. 2006; Hou et al. 2013). Aside from temporal variation and precipitation data accuracy, water yield' interactions with other services

are determined by the definition of this service. In our study, water yield is defined as the difference between precipitation and ET and is thus negatively correlated with ET at the pixel scale (Fig. 3). However, when water supply is defined as a fraction of precipitation (Yang et al. 2015) or groundwater recharge (Qiu and Turner 2013), it is significantly positively correlated with regulating services.

Our study found significant positive correlations among habitat quality, NPP, ET, and recreation capacity at the pixel scale. These findings support the idea that synergies are common among regulating and cultural services (Raudsepp-Hearne et al. 2010; Kandziora et al. 2013; Xue et al. 2015). Moreover, in this study, the significance of these synergies changed between the beginning of the first phase of the GGP and after the program had come to an end. For example, the correlations between habitat quality and ET and between NPP and recreation capacity were stronger in 2010 than in 2000 (Fig. 3). Jia et al. (2014) and Zheng et al. (2014) obtained similar results, as they observed changes in the synergies among regulating services between the beginning of the first phase of the GGP and after the program had ended. The changes in the synergies were due in large part to the implementation of the GGP, rather than to climate change, as the study area' climate did not present a clear changing trend, instead fluctuated throughout 2000 and 2010 (Yang et al. 2014). The GGP not only altered land use composition in the land retirement area (Table 1 in this article, also see Jia et al. 2014), but also significantly changed the capacity of different land use classes to provide ecosystem services (Fig. 2, Table 2, also see Jia et al. 2014), particularly enhancing the regulating and habitat services supplied by tree and grass based land uses. Furthermore, farmland retirement in the Baota District was mostly accomplished before 2005 and only small areas of woodland, grassland and farmland altered from 2005 to 2010 (Table 1). Meanwhile, the changes in the two regulating services and habitat quality for the three land use types were similar to the changes in the area of the land use types, which experienced far greater changes between 2000 and 2005 than between 2005 and 2010 (Fig. 2). This phenomenon offers further evidence indicating that the GGP served as the main cause of the changes observed in these regulating and habitat services and consequently altered the synergies between the services.

The quantification of recreation service requires socioeconomic data at a fine spatial scale (Anderson et al. 2009). Recreation potential or recreation capacity is used as a proxy of this service when socioeconomic data are inadequate (Burkhard et al. 2014; Yang et al. 2015). Consequently, different definitions and formulations of this service lead to distinct results. Many previous studies on recreation capacity at the global, national or even regional scales merely considered land use/cover type as the influencing factor (Costanza et al. 1997; Xie et al. 2008; Li et al. 2010; Koschke et al. 2012; Wu et al. 2013). However, different regions have distinct geographical and biophysical properties, even for the same land use; recreation capacity is thus impacted by additional factors. In this study, we understood recreation capacity to refer to suitability for locals to carry out recreational activities. We referred to the assumptions of Schröter et al. (2014) and Haines-Young et al. (2012), and considered two important environmental features of the study area, the rugged landform and the low vegetation coverage. Therefore, we selected land use type, slope, vegetation coverage, and landscape diversity as the most influential factors for the study area's recreation capacity. As a result, even for the areas of the same land use type, those with smaller slopes, greater vegetation coverage, and higher landscape diversity are more suitable for locals' recreational activities. The results show a high spatial consistency between this service and the two regulating and one habitat services. Spatial agreement between recreation service and regulating services is reported by other researchers in the literature as well (Raudsepp-Hearne et al. 2010; Yang et al. 2015). Moreover, the results indicate that woodland generally has the highest recreation capacity, followed by residential areas and grassland. However, our findings do not agree with those of Lauf et al. (2014), who identified population density and close-to-home green spaces as determining factors of the service. As ecosystem service researchers have yet to agree on the proxy of recreation service, they should be cautious when defining this proxy and ensure that the formulation of the proxy is understandable and suitable to the study area.

Another interesting phenomenon we found is that some ecosystem service interactions in this study changed across spatial scales. For example, food productivity served as a significant trade-off to NPP,

ET, and recreation capacity at the pixel scale in 2000 and 2010 (Fig. 4) because farmland was the only land use type generating food, but it provided much less of the two regulating and one cultural services compared to woodland (Fig. 2). These two land use types accounted for over 60% of the study area in 2000 and 2010. However, the significance of this correlation decreased significantly, and at times, the correlation even changed to a positive one at the town scale. A probable reason for this phenomenon is that when pixels were aggregated to towns, the composition and configuration of different land use types determined the area-averaged ecosystem services of the towns. For example, the Nanniwan town in the southwestern region of the Baota District had a low cropland coverage and a high coverage of forest. Therefore, NPP per land area was high in this town; meanwhile, the town had a moderate food production per land area due to a high food productivity on cropland. Consequently, the tradeoff between food productivity and NPP was not significant in Nanniwan. In terms of the significance changes of ecosystem services correlations across the pixel and town scales, the variation of sample size for correlation analysis also made contributions. This study used sample sizes of 3270 (3270 1 km$^2$ pixels) and 19 (19 towns) for the pixel and town scales, respectively. Consequently, the significance can greatly decrease from the pixel scale to the town scale even though the correlation coefficient at the town scale is close to or larger than that at the pixel scale (e.g., the correlations between habitat quality and NPP and between habitat quality and ET in 2010, see Fig. 4). The result of the spatial scale dependency of ecosystem service interactions is consistent with the findings of Felipe-Lucia et al. (2014), who investigated ecosystem service correlations at the patch, municipality and landscape scales in the floodplain of the Piedra River in central Spain. For example, in their findings, significant interactions exist between food production and local climate change at the municipality and landscape scales but not at the patch scale. The spatial scale-dependent feature of ecosystem service interactions is the result of the scale dependency of ecosystem service provider and beneficiary, and of ecosystem service measurement and management (Zhang et al. 2013). This finding suggests the importance of scientists and decision makers' awareness of the scale issue when measuring and managing ecosystem services (Anderson et al. 2009). In terms of

ecosystem service measurement, each service has a most significant spatial scale. For instance, with respect to measuring the six services involved in this study, the most significant spatial scale for food productivity is administrative unit, for water yield is watershed, for habitat quality, NPP, and ET is pixel, and for recreation capacity is landscape. Measuring food productivity is most feasible on the scale of administrative unit because accurate food production data for administrative units of different levels can be obtained from the government. Watershed is the most practical scale to measure water yield because the boundary of the most important ecological processes the service relies on, e.g. runoff generation and water accumulation, coincide with the boundary of watershed (Tallis et al. 2013). Habitat quality, NPP, and ET can be measured on the pixel scale because grid spatial data used for modeling these services (e.g., land use maps for modeling habitat quality, NDVI data for calculating NPP, and air temperature data for modeling ET) can be produced through interpretation of remote sensing images and interpolation of meteorological data from monitoring stations. Landscape is the most suitable scale to measure recreation capacity because the biophysical properties of landscape, such as land cover type and configuration, vegetation type variety, and terrain and landform, determine the potential of landscape to provide recreational service to humans (Schröter et al. 2014). The spatial scale dependency of ecosystem service interactions additionally implies that ecosystem service managers may reduce trade-offs between certain provisioning and regulating services and enhance synergies between various regulating services when they adapt polices and managements to the respective suitable spatial scales.

In addition to spatial scales, ecosystem service interactions may change across temporal scales. We only quantified ecosystem services and service interactions for the Baota District on the annual scale in this study. In fact, the interaction patterns of services may be different on shorter temporal scales, such as monthly and seasonal scales due to intra-annual variations of ecosystem service supplies and on longer temporal scales, such as years or decades, because the provision of the services needs longer time than 1 year (Burkhard et al. 2014). Water yield is a typical service showing intra-annual variation characteristics. As for our study area, the precipitation in the Baota District is

negligible in winter (account for 2–3% in the annual precipitation, see Wang et al. 1995), and water yield in winter is mostly determined by evapotranspiration. As a consequence, the interaction patterns between water yield and other services in winter should differ from those for the whole year. In addition, seasonal patterns can be found for some regulating (e.g., flood control in rain season, see Vigerstol and Aukema 2011) and cultural services (e.g., tourism service in tourist season). Therefore, researchers have to carefully select appropriate temporal scales when measuring ecosystem services and service interactions.

## Conclusions

We found considerable changes in the composition of land use in the Baota district that resulted from the Grain for Green Program (GGP). The program altered food productivity, water yield, habitat quality, NPP, ET, and recreation capacity of different land use types in different degrees, for example, greatly enhanced the two regulating and one habitat services over the years. Noticeable changes in the spatial distributions of the six services are observed between 2000 and 2010 in the research area, and interactions among these services changed in varying degrees from the beginning of the GGP to the time after the program had come to an end of its first phase. Furthermore, the majority of the ecosystem service interactions in this study changed, either in direction or in significance across the pixel scale and the town scale. Our study supports the idea that no single relevant scale exists at which to analyze ecosystem service interactions. Moreover, our work can increase the understanding of the temporal variation of ecosystem service interactions caused by regional ecological restoration program, and the spatial scale dependency of ecosystem service interactions. The results suggest the importance of scientists and decision makers' awareness of the temporal variation and spatial scale dependency of ecosystem service interactions when measuring and managing ecosystem services. Such awareness may help to reduce trade-offs between provisioning and regulating services and enhance synergies between various regulating services in regional ecosystem management. Further research may focus on examining interactions among more ecosystem service types and research areas with

different physical and socioeconomic contexts and multiple spatial extents.

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