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GIS-based Analysis for Hotspot Identification of Tradeoff Between Ecosystem Services: A Case Study in Yanhe Basin, China

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Abstract: Although the quantification and valuation of ecosystem services have been studied for a long time, few studies have specifically focused on the quantification of tradeoffs between ecosystem services and tradeoff hotspots. Based on previous studies of ecosystem service assessment, we proposed a feasible method to analyze the tradeoffs between ecosystem services, including determination of their relationship, quantification of tradeoffs, and identification of tradeoff hotspots. Potential influencing factors were then further analyzed. The Yanhe Basin in the Loess Plateau was selected as an example to demonstrate the application process. Firstly, the amounts of net primary production (NPP) and water yield (WY) in 2000 and 2008 were estimated by using biophysical models. Secondly, correlation analysis was used to indicate the tradeoffs between NPP and WY. Thirdly, tradeoff index ($TI_{\mathrm{NPP/WY}}$) was established to quantify the extent of tradeoffs between NPP and WY, and the average value of $TI_{\mathrm{NPP/WY}}$ is 24.4 g/(mm·m^2) for the Yanhe Basin between 2000 and 2008. Finally, the tradeoff hotspots were identified. The results indicated that the area of lowest tradeoff index concentrated in the middle part of the Yanhe Basin and marginal areas of the southern basin. Map overlapping was used for preliminary analysis to seek potential influencing factors, and the results showed that shrub was the best suited for growing in the Yanhe Basin, but also was a potential influencing factor for formulation of the tradeoff hotspots. The concept of tradeoff index could also be used to quantify the degree of synergy between different ecosystem services. The method to identify the tradeoff hotspots could help us to narrow the scope of study area for further research on the relationship among ecosystem services and concentrate on the potential factors for formation of tradeoff between ecosystem services, enhance the capacity to maintain the sustainability of ecosystem.

Keywords: correlation analysis; net primary productivity; water yield; tradeoff index; influencing factor

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1 Introduction

Ecosystem services are the basis for the survival and sustainable development of human society (Costanza *et al.*, 1997; Daily, 1997). However, the relationship between ecosystem services is not always synergistic (Foley *et al.*, 2005), and tradeoffs exist mainly between provision and regulating services such as food production and soil conservation (Power, 2010). People often hope to maximize one or several kinds of ecosystem services by changing land use (Gasparatos *et al.*, 2011; Karp *et al.*, 2013), but it usually triggers the interaction between different ecosystem services (Smith *et al.*, 2013). Tradeoffs between ecosystem services often lead to some unpleasant results for human society, namely presenting a zero-sum game for the two ecosystem services both of which people need (Zheng *et al.*, 2014), and one of them may decay irreversibly in the interaction with each other (Dobson *et al.*, 2006). As a result, people have to make tough decisions to manage

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the allocation of ecosystem services (Ferraro and Hanauer, 2011). Hence, it is necessary to exactly identify the relationship between ecosystem service and where the serious tradeoffs take place.

The exploration of relationship between ecosystem services should be based on the quantification of ecosystem services (Sagoff, 2011). In order to make people conscious of the significance and benefits of ecosystem services, plenty of studies have assessed the physical quantity of ecosystem services, and then valued them (Fu *et al.*, 2011b; Carreno *et al.*, 2012). There have been many models and methods to realize the quantification (Logsdon and Chaubey, 2013) and to value ecosystem services (Curtis, 2004; Abson and Termansen, 2011), such as Revised Universal Soil Loss Equation (RUSLE) (Fu *et al.*, 2011a), Carnegie-Ames- Stanford Approach (CASA) (Cramer *et al.*, 2001), Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998) and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Nelson *et al.*, 2009). Remote sensing provides an effective tool to conduct spatially explicit assessment for ecosystem services, for instance, mapping ecosystem service supply and demand (Burkhard *et al.*, 2012), and valuation of ecosystem service in metropolitan area (Kreuter *et al.*, 2001) or coastal wetland (Zhao *et al.*, 2004). Furthermore, through correlation analysis (Jopke *et al.*, 2015) and ecosystem service bundles as the sets of services that appear together repeatedly (Raudsepp-Hearne *et al.*, 2010), the relationship between ecosystem services also has been determined qualitatively in previous case studies (Turner *et al.*, 2014; Yang *et al.*, 2015). However, little attention has been paid to the quantification of the extent of tradeoff between ecosystem services, especially in a clear and concise way. Meanwhile, the hotspots of ecosystem services, in which the value of specific ecosystem service is much higher than elsewhere, have been reported in some literatures (Jiang *et al.*, 2013; Wu *et al.*, 2013), but the tradeoff hotspot between ecosystem services has been little discussed whereby the tension of tradeoff is much more serious. Although Qiu and Turner (2013) attempted to identify the place that the strongest relationship among ecosystem services happened, ecosystem services data employed in the study was limited to only one given year (Qiu and Turner, 2013), meaning a point of time. As the tradeoff between ecosystem services is a dynamic process in response to certain drivers (Bennett *et al.*, 2009), and it should be observed and evaluated over a period of time (Bryan, 2013). Therefore, we proposed a method to analyze the tradeoff hotspot between ecosystem services, including determination of relationship, quantification of tradeoff, and identification of tradeoff hotspot between ecosystem services. In the range of tradeoff hotspots, the mechanism and influencing factors on formation of tradeoff could be probed more easily and distinctly. To illustrate our method, we selected the Yanhe Basin, which is located in a semi-arid area, as a case study area.

In semi-arid regions, the ecological balance is usually fragile, owing to the combined effect of climatic change and anthropogenic activities (Feng *et al.*, 2013), and it is urgent to strengthen ecosystem services through revegetation (Lu *et al.*, 2012). The Yanhe Basin was also confronted with these challenges prior to the 1990s, thus the government implemented a large scale revegetation project using financial support and administrative measures. In the process of vegetation construction, the changes for different ecosystem services appear various (Wang *et al.*, 2011a; Lu *et al.*, 2012): some services have increased, such as net primary production (NPP), and some have declined, for instance, water yield (WY). There seems a potential tradeoff between those ecosystem services in the Yanhe Basin. Net primary production is one of the key supporting services in landscape (Pan *et al.*, 2014). Enhancing the capacity of net primary production is very important to maintain the biodiversity (Costanza *et al.*, 2007) and other ecosystem services (Carreno *et al.*, 2012). Restoring vegetation can effectively enhance the net primary production. Water yield is also a kind of major ecosystem service (Brauman *et al.*, 2007). Sufficient amount of WY serves as a vital water source for the functioning of ecosystem, residents living and economic development (Little *et al.*, 2009). Consequently, we performed a case study on the relationship between NPP and WY in the Yanhe Basin to explain how to identify a tradeoff hotspot.

2 Materials and Methods

2.1 Study area

The Yanhe Basin (36°23'–37°20'N, 108°39'–110°30'E) is located in the middle part of the Loess Plateau (Fig. 1).

With an average annual precipitation of 496 mm, the study area is classified as a forest steppe zone for the pivotal natural vegetation and semi-arid area for climatic zones. With an area of 7650 km^2, 90% of the Yanhe Basin is the loess hilly area, and the average annual temperature varies from 8.8℃–10.2℃. From the southeast to northwest, the elevation slightly increases and the average annual precipitation gradually decreases. In the long-term history, the Yanhe Basin has experienced severe destruction of vegetation and soil erosion due to the combined effect of human activities and climatic factors. Since 1999, revegetation measures have been implemented in the Yanhe Basin, as a part of Grain to Green Project (GGP) in China. With the recovery of vegetation, the main ecosystem services in study area are expected to experience a significant change, such as net primary productivity and water yield.

2.2 Quantification of ecosystem services

The physical quantities for NPP and WY were assessed using biophysical models. The analysis of relationship between them was based on the quantification of NPP and WY.

2.2.1 Net primary productivity (*NPP*)

Through photosynthesis, plants absorb carbon dioxide and water to produce glucose and oxygen (Sitch *et al.*, 2003). During this process, the plant utilizes the photosynthetic active radiation (APAR). The NPP is used to represent the amount of carbon fixed by plants and accumulated as biomass (Zhao and Running, 2010). In the model proposed by Carnegie-Ames-Stanford Approach (CASA) (Potter *et al.*, 1993), the NPP is estimated utilizing the information of APAR and the light use efficiency, deduced from remote sensing data (Field *et al.*, 1998; Gower *et al.*, 1999). The formulas for calculating NPP are expressed below:

$$NPP(t) = APAR(t) \times \varepsilon(t) \tag{1}$$

$$APAR(t) = PAR(t) \times FPAR(t) \tag{2}$$

$$\varepsilon(t) = \varepsilon^* \times T_1(t) \times T_2(t) \times W(t) \tag{3}$$

where $APAR(t)$ is the canopy-absorbed incident solar radiation (MJ/m^2) in time t, $\varepsilon(t)$ is the actual light use efficiency (g/MJ) in time t; $PAR(t)$ is the total incident photosynthetically active radiation (MJ/m^2) in time t, $FPAR$ is the fraction of PAR absorbed by vegetation canopy; ε^* is the maximum light use efficiency (g/MJ), T_1 and T_2 are temperature stress coefficients, and W is the water stress coefficient.

The formulas for calculating $FPAR$, T_1, T_2 and W are

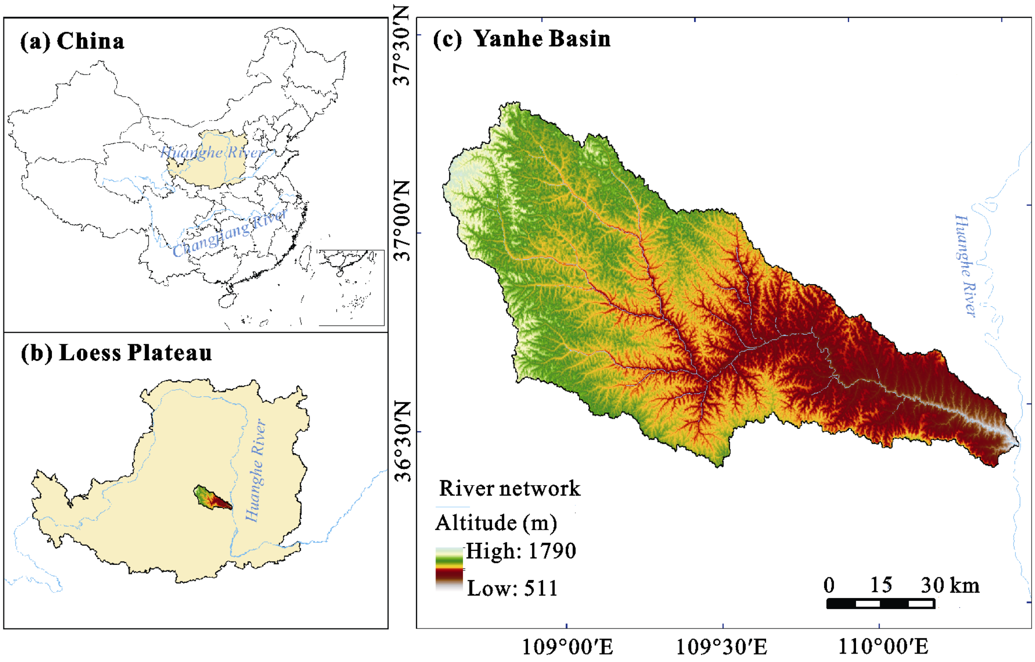

Fig. 1 Location of study area. (a) Loess Plateau; (b) Yanhe Basin; (c) digital elevation model (DEM) of study area

expressed below (Field *et al.*, 1995; Xu *et al.*, 2006; Xiong *et al.*, 2010):

$$FPAR = \frac{(SR - SR_{\min}) \times (FPAR_{\max} - FPAR_{\min})}{SR_{\max} - SR_{\min}} + FPAR_{\min} \tag{4}$$

$$SR = \frac{1 + NVDI}{1 - NVDI} \tag{5}$$

There is a linear relationship between simple ratio (*SR*) and *FPAR*. $FPAR_{\min}$ and $FPAR_{\max}$ are set to 0.001 and 0.95, separately (Xu *et al.*, 2006). The Normalized Different Vegetation Index (*NDVI*) is the normalized difference vegetation index. The $SR_{\min}$ and $SR_{\max}$ are related to vegetation types and set to 5% and 95% quantiles of *NDVI* in the corresponding type of vegetation, respectively.

$$T_1 = -0.0005(T_{\text{opt}} - 20)^2 + 1 \tag{6}$$

$$T_2 = \frac{1}{1 + \exp\{0.2(T_{\text{opt}} - 10 - T_{\text{mon}})\}} \times \frac{1}{1 + \exp\{0.3(-T_{\text{opt}} - 10 + T_{\text{mon}})\}} \tag{7}$$

where T_{opt} is the air temperature in the month when the *NDVI* reaches its maximum for the year, and T_{mon} is the average air temperature in the month (Potter *et al.*, 1993; Xu *et al.*, 2006).

$$W(t) = \frac{EET(t)}{PET(t)} \tag{8}$$

where *EET*(*t*) and *PET*(*t*) are the estimated evapotranspiration and potential evapotranspiration in the month (mm), and could be calculated using ETWatch (Xiong *et al.*, 2010; Wu *et al.*, 2012).

2.2.2 Water yield (WY)

The calculation of the water yield service is determined by the difference between annual precipitation (*PPT*) and annual total water loss.

$$WY = PPT - ET \pm \Delta S \tag{9}$$

where *ET* is the annual evapotranspiration, ΔS is the annual change in soil water storage.

Because the average depth of loess reaches 50–80 m in Loess Plateau and climatic condition is semi-arid in study area (Wang *et al.*, 2011c), soil water deficit results from higher evapotranspiration than the precipitation infiltration (Li *et al.*, 2014), and the effect of surface infiltration on permanent groundwater table is very limited (Tu *et al.*, 2009). In order to simplify the model calculation, this study assumes that soil water would be stable between the normal years in which the annual precipitation is similar. Resulting from the assumption and the dominant role of surface runoff in stream flow of Loess Plateau, the annual changes of soil water and groundwater would not be large, and ΔS is negligible in this study (Feng *et al.*, 2012). Consequently, the formula to calculate the water yield service in study area is expressed as:

$$WY = PPT - ET \tag{10}$$

The ET is controlled by several key environmental factors, including available energy, water and seasonal vegetation biomass dynamics (Sun *et al.*, 2011). Through model calibration and validation, the ET could be evaluated as follow (Feng *et al.*, 2012):

$$ET = 9.78 + 0.0072 \cdot PET \cdot PPT + 0.05142 \cdot PPT \cdot LAI \tag{11}$$

where *LAI* is the leaf area index, and *PET* is the potential evapotranspiration deduced from a simpler Hamon *PET* method (Hamon, 1963) as below:

$$PET = 0.1651 \cdot Ld \cdot RHOSAT \cdot Nd \tag{12}$$

$$Ld = \arccos(-\tan\psi \tan\delta) \tag{13}$$

$$\delta = 0.4093 \times \sin(2\pi / 365) \times J - 1.405 \tag{14}$$

$$RHOSAT = 216.7 \cdot ESAT / (T + 273.3) \tag{15}$$

$$ESAT = 6.108 \cdot \mathrm{EXP}(17.26939 \cdot T / (T + 237.3)) \tag{16}$$

where *Ld* is the average daytime length of each month, *RHOSAT* is the saturated vapour density at mean monthly air temperature; *ESAT* is the saturated vapour pressure at the given *T*; and *Nd* is the day number of each month. ψ is the latitude, δ is the solar declination and *J* is the Julian day.

2.3 Determination of relationship and tradeoff index (TI)

We estimated the correlation between two kinds of ecosystem services to determine their relationship (Jopke *et al.*, 2015). Based on the different time series data, the correlation analysis described different meanings for the relationship between a same pair of ecosystem services (Zheng *et al.*, 2014). The correlation coefficients for a given period represent the dynamic interactive relationship between ecosystem services, namely tradeoff or synergy.

Assuming that there are two kinds of ecosystem services in landscape, we are expecting a contrasting trend between the two ecosystem services; that is, the ecosystem service A (ES_A) increases while ecosystem service B (ES_B) decreases. Correlation analysis could be used to determine whether the relationship between them is tradeoff or not. Following the determination of tradeoff between the two ecosystem services, we established a proxy to quantify its extent, which is called tradeoff index.

Tradeoff Index (TI) is defined as how many units the ES_A increase when decreasing a unit ES_B, and can be estimated by

$$\mathrm{TI}=\frac{ES_{\mathrm{A}}(T+\Delta t)-ES_{\mathrm{A}}(T)}{ES_{\mathrm{B}}(T)-ES_{\mathrm{B}}(T+\Delta t)} \tag{17}$$

where $ES_A(T + \Delta t)$ and $ES_B(T + \Delta t)$ refer to the amounts of ecosystem service A and ecosystem service B at time $(T + \Delta t)$ in landscape, while $ES_A(T)$ and $ES_B(T)$ refer to the amounts of ecosystem service A and ecosystem service B at time T.

In this paper, tradeoff index between net primary productivity and water yield are expressed as $TI_{\mathrm{NPP/WY}}$ (g/(mm·m^2))—which means how many units of *NPP* increment would appear when decreasing a unit water yield, and can be estimated by

$$\mathrm{TI}_{\mathrm{NPP/WY}}=\frac{NPP08-NPP00}{WY00-WY08} \tag{18}$$

where *NPP*00 (g/m^2) and *WY*00 (mm) are the amounts of net primary productivity and water yield in the year of 2000 in the Yanhe Basin, *NPP*08 (g/m^2) and *WY*08 (mm) are the amounts of net primary productivity and water yield in the year of 2008 in the Yanhe Basin.

The coefficients of correlation and $TI_{\mathrm{NPP/WY}}$ were calculated by ArcGIS software (ArcGIS 9.3).

2.4 Data collection and processing

Data needed in ecosystem model include land cover, NDVI, and climate data. We extracted land covers for the Yanhe Basin in 2000 and 2008 from Landsat TM/EM. There are seven kinds of land covers in the Yanhe Basin, including forest land, shrub land, grass land, farm land, residential land, water area and abandoned land. Forest, shrub and grass were selected as the main revegetation type in GGP. The 1-km and monthly Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data from 2000 to 2008 were acquired from the MODIS Land Processes Distributed Archive Center (http://wist.echo.nasa.gov/api). Meteorological data were interpolated to a 1-km resolution, collected from 172 weather stations within and near the study area. The meteorological data included solar radiation, air temperature precipitation, daytime length and relative humidity during 2000–2008.

3 Results and Analyses

3.1 Changes in annual NPP over Yanhe Basin

The spatial variation of annual NPP in the study area is displayed (Fig. 2). In 2008, there is a clear ascending trend was shown from the northwest to the southeast, while no obvious trend could be seen in 2000. For the whole basin, a significant increment of NPP occurred from 2000–2008 (Fig. 3), especially in the central and southeastern regions. The total annual NPP increased from 1.5×10^{12} g C in 2000 to 3.3×10^{12} g C in 2008, and the average annual NPP also increased to 430.4 g C/m^2 which is even more than twice the value in 2000. The result was in line with some previous reported studies in the Yanhe Basin. For example, Song *et al.* (2009) estimated the vegetation net primary productivity on North Shaanxi Loess Plateau in which the Yanhe Basin is the main part and the average value of NPP was 447.3 g C/(m^2·yr) in 2005 (Song *et al.*, 2009). Li *et al.* (2011) analyzed the variation of vegetation net primary productivity in Shaanxi Province during 2000–2008 where the Yanhe Basin is located, and the annual NPP ranged between 340–434 g C/m^2 (Li *et al.*, 2011). Yuan *et al.* (2014) modeled the net primary productivity of terrestrial ecosystem in China, and the value of average annual NPP in the Yanhe Basin was 300–500 g C/m^2 in 2005 (Yuan *et al.*, 2014). Other studies also indicated that NPP showed a continuously increasing trend in the Yanhe Basin or most area of Loess Plateau during 2000–2008 (Su *et al.*, 2012; Su and Fu, 2013; Xie *et al.*, 2014).

The total annual NPP for forest, shrub and grass were 1.7×10^9 g C, 3.12×10^9 g C and 2.167×10^{10} g C in 2008, which increased by 91.2%, 139.8% and 242.7%

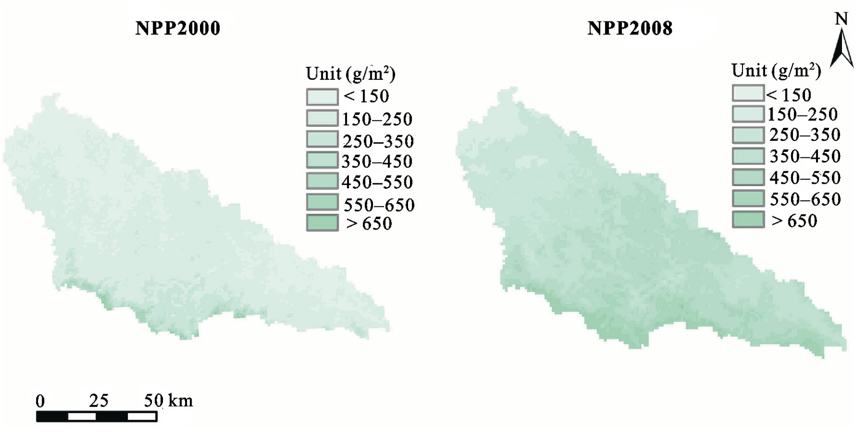

Fig. 2 Net primary productivity (NPP) in the Yanhe Basin

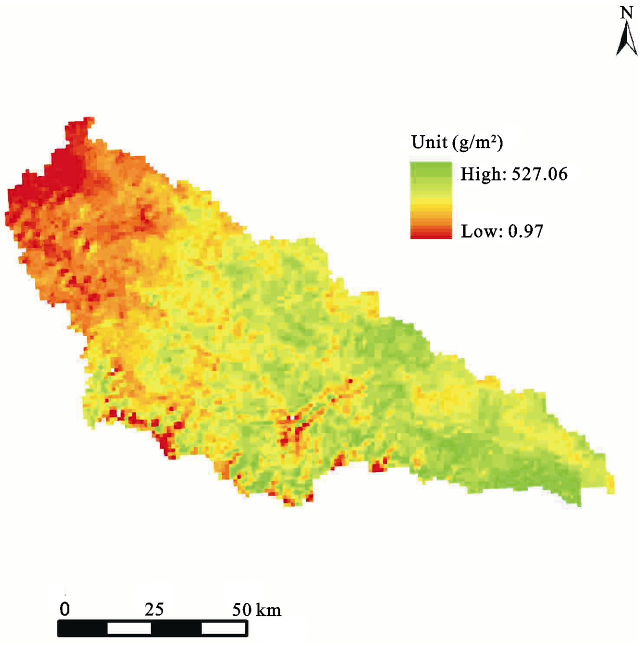

Fig. 3 Change of net primary productivity (NPP) in Yanhe Basin during 2000–2008

during 2000–2008, respectively. The annual NPP for forest, shrub and grass in 2008 were 499.7 g C/m^2, 512.4 g C/m^2 and 418.8 g C/m^2, respectively. Feng *et al.* (2013) calculated the annual NPP in each bioclimatic zones in the Loess Plateau, and reported the annual NPP for forest, shrub and grass in the bioclimatic zone of semi-arid forest-grasslands (FOR-GRASS) were 402.6 g C/m^2, 439.4 g C/m^2 and 429.8 g C/m^2 in 2008, respectively. It is worth noting that the Yanhe Basin is located in FOR-GRASS zone (Feng *et al.*, 2013).

Different vegetation types are better suited for corresponding bioclimatic zone in the Loess Plateau (Feng *et al.*, 2013). For the Yanhe Basin, in the top 20% NPP area, which contains 45% of the whole basin shrub land, 36% of forest and 14% of grassland, shrub land has the highest value. It means that almost half of all shrub land located in the area in which plants grow well.

3.2 Changes in annual water yield (WY) over Yanhe Basin

The spatial distribution of ecosystem service for annual water yield in the Yanhe Basin is shown in Fig. 4. Both in 2000 and 2008, there is an increasing trend in the annual water yield from the southeast to the northwest. A decreasing trend for water yield was shown in the whole basin from 2000–2008 (Fig. 5). The total annual water yield decreased from 2.581 × 10^8 m^3 in 2000 to 1.562 × 10^8 m^3 in 2008. The average annual water yield also decreased to 20.4 mm which is almost the half value in 2000, especially in marginal areas of the southern part. By comparison, the annual precipitation in 2000 was 358 mm in the Yanhe Basin, and the value in 2008 was 396 mm, which is a little higher than its value in 2000. The result of calculation for water yield is also similar to previous researches in the Yanhe Basin. Ren *et al.* (2012) conducted a research on the runoff and sediment in the the Yanhe Basin from 1961–2008, and found there was also an increasing trend in annual precipitation and a decreasing trend in annual runoff during the period of 1991–2000 and 2001–2008 (Ren *et al.*, 2012). Based on data collected from hydrological station, Zhao *et al.* (2014) reported a continuous decline for the runoff depth in the Yanhe Basin since 1997, and the average value of annual runoff depth was 24.76 mm between 1997 and 2010 (Zhao *et al.*, 2014). The decline

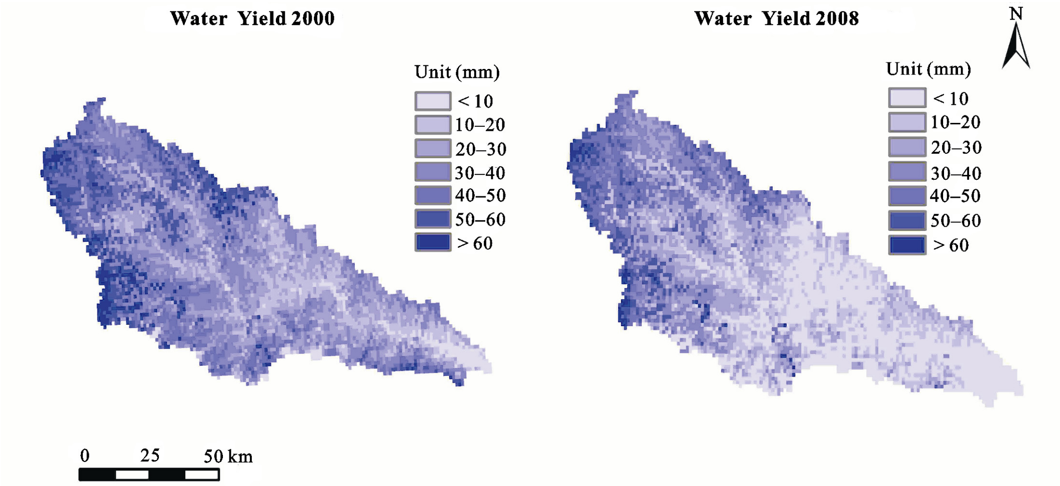

Fig. 4 Water yield in Yanhe Basin

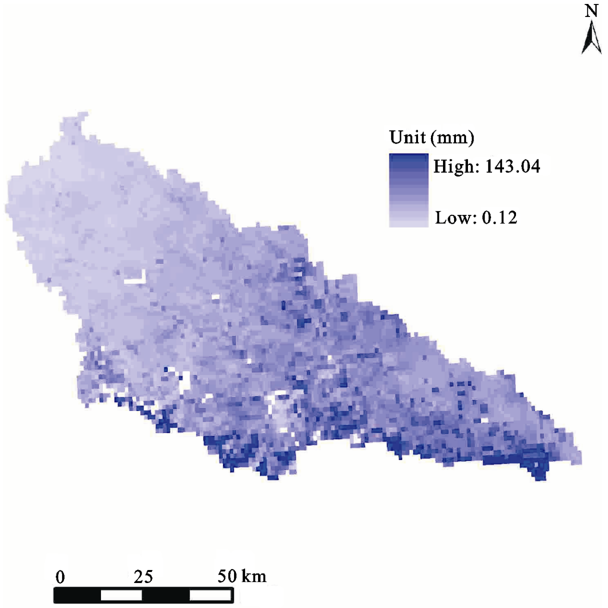

Fig. 5 Change of water yield in the Yanhe Basin during 2000–2008

trend of water yield in the study period was also confirmed in the Loess Plateau (Wei *et al.*, 2015).

The total annual water yields for forest, shrub and grass were 5×10^6 m^3, 6.5×10^6 m^3 and 1.15×10^8 m^3 in 2008, and the number decreased respectively by 55.50%, 57.00% and 4.39% during 2000–2008, and the average values were 14.4 mm, 10.9 mm and 22 mm, respectively.

For the spatial distribution, the reduction of annual WY showed an increasing trend from the northwest to the southeast which is opposite to the spatial distribution of annual water yield, indicating low-water yield areas appear to have lost water yield at a greater rate, at least during the period of 2000–2008. Such variations in annual water yield led to a more significant imbalance in the distribution of water resources in the interior basin.

4 Discussion

4.1 Relationship between NPP and WY over Yanhe Basin

The correlation analysis could be used to help determine the relationship between ecosystem services (Laterra *et al.*, 2012; Wu *et al.*, 2013). Positive correlation coefficient signifies two kinds of ecosystem services change in the same direction, could be seen as synergy; reversely, negative correlation coefficient signifies that two ecosystem services change in the opposite direction, deemed as a tradeoff (Zheng *et al.*, 2014). Tradeoff is defined as a situation which may arise from a simultaneous response to the same driver or due to a real interaction among services (Bennett *et al.*, 2009). Hence, when the relationship between two ecosystem services is determined as a tradeoff, it does not mean that there must be a causal relationship between the two, and it may be derived from a response to the same driver such as land use change.

In 2000, 2008 or 2000–2008, the correlation coefficients between NPP and water yield are all negative (Table 1), therefore the tradeoff exists between NPP and water yield. During the period of 2000–2008, the correlation coefficient between NPP and WY is changed drastically from –0.063 to –0.538. Such change is the

Table 1 Correlation coefficient for each pair of ecosystem services

	NPP00	NPP08	WY00	WY08	NPP00-08	WY00-08
NPP00	1	0.6906	–0.0633	–0.2577	0.0025	–0.4139
NPP08		1	–0.2455	–0.5380	0.7234	–0.6730
WY00			1	0.8454	–0.2782	0.1955
WY08				1	–0.4959	0.6819
NPP00–08					1	–0.5345
WY00–08						1

Note: $P < 0.01$ for all of the correlation coefficients between ecosystem services

result of a combined effect of two factors. One is the tradeoff between NPP and water yield in the whole basin, and the other is asymmetric decline for annual WY in the southern and northern basin, whereby the low water yield area reduced more. In correlation analysis, the coefficient between WY00 and WY08 is relatively high; illustrating the spatial distribution of annual water yield has no significant change across the whole basin. The result confirmed that the places in which higher annual water yield appears in 2000 still generates more runoffs in 2008.

The tradeoff between NPP and water yield has been illustrated in other researches related to the effect of vegetation on hydrological process in the Yanhe Basin (Yang *et al.*, 2004; Wang *et al.*, 2011b; Ran *et al.*, 2014; Zhao *et al.*, 2014). Su and Fu (2013) studied the relation among ecosystem services in the Loess Plateau from 1990 to 2008, and the results also showed that there is a tradeoff between NPP and WY.

4.2 Tradeoff index between NPP and water yield over Yanhe Basin

When the relationship between two ecosystem services was defined as tradeoff, the extent of its interchange could be quantified by a simple ratio called tradeoff index. Tradeoff index is the ratio of the amount of change between the two ecosystem services, and is used to illustrate the degree of sensitivity in response to the change of each other. In this paper, the tradeoff index between NPP and WY ($TI_{\mathrm{NPP/WY}}$) is similar to the concept of cost-effectiveness analysis, which means the number of unit NPP increments realized when a unit WY is decreased.

The $TI_{\mathrm{NPP/WY}}$ ranges from 0.1–1588.7 g/(mm·m^2) across the the Yanhe Basin (Fig. 6), and the average value is 24.4 g/(mm·m^2), representing that the decrement of a millimeter in water yield occurred and synchronously an increment of 24.4 g C NPP occured in each square meter. Generally, the spatial distribution of $TI_{\mathrm{NPP/WY}}$ presents an increasing trend from the southeast to northwest, and is opposite to the variation trend for changes of NPP and WY. If the value of $TI_{\mathrm{NPP/WY}}$ is higher, it means that a certain amount of growth in NPP just need less loss in WY and would be better for local ecosystem in semi-arid area.

4.3 Identification of tradeoff hotspot over Yanhe Basin

As an indispensable water source, water yield is the basis for ecological balance and sustainable development of human society (Xu *et al.*, 2005; Fang *et al.*, 2007), especially in downstream areas. Due to the tradeoff between NPP and WY, it is necessary to focus on the regions called tradeoff hotspot with insufficient WY in 2000 and also had low $TI_{\mathrm{NPP/WY}}$ in the process of

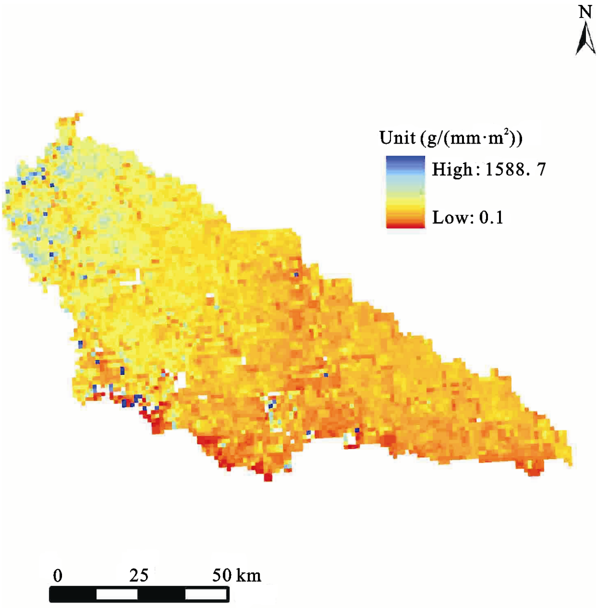

Fig. 6 Spatial distribution of TI between NPP and water yield in the Yanhe Basin during 2000–2008

GGP during 2000–2008. Specifically, in this paper, the tradeoff hotspot is defined as a place with lowest 20% water yield and lowest 20% The $TI_{\mathrm{NPP/WY}}$, meeting two conditions simultaneously.

There is a relatively clear relationship between tradeoff hotspots and their geographical location. The tradeoff hotspots were concentrated in the middle part of the Yanhe Basin and marginal areas of southern basin (Fig. 7).

In order to better understand the possible reasons for the formation of tradeoff hotspots, some methods to quickly conduct the preliminary analysis should be adopted. Overlaying between maps of tradeoff hotspots and other potential influencing factors would be an effective way to narrow the scope of study area for further research, especially in a large scale. For instance, we overlapped the tradeoff hotspots with land use map in 2008, as the drastically changing land use was considered as a major driver to change the ecosystem service in the Yanhe Basin during 2000–2008.

In the tradeoff hotspot area, which contains 30.2% of the whole basin shrub land, 14.7% of forest and 7.2% of grassland, shrub land has the highest value, meaning that the location of the shrub has a relatively greater likelihood to be a tradeoff hotspot. Compared to forest and grass, shrub land displayed a lower The $TI_{\mathrm{NPP/WY}}$ in the study area, meaning that water yield decreased more quickly and NPP increased less than elsewhere. Shrub seems to be a potential influencing factor to exacerbate the tension of water shortage in the Yanhe Basin and is worth further field research to study the effect of shrub on water yield (Wang *et al.*, 2008). The tradeoff hotspots also could be overlapped with other maps such as distributions of slope or precipitation, to explore the potential influencing factors. Then, the further field investigation need to focus on the relationship between the tradeoff hotspots and the potential influencing factors.

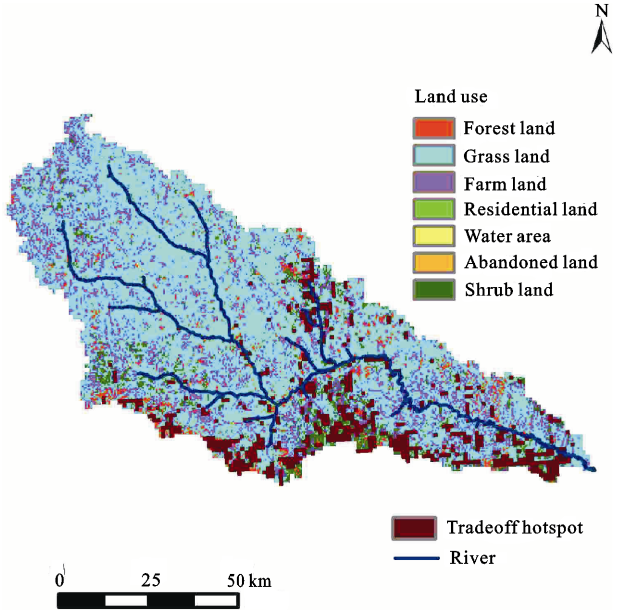

Fig. 7 Spatial distribution of tradeoff hotspots in Yanhe Basin during 2000–2008

In short, the identification of tradeoff hotspots and overlapping maps of potential influencing factors could help us to make a preliminary analysis on the tradeoff between two ecosystem services and their potential causes to formulate tradeoff hotspots, enhance the capacity to maintain the sustainability of vegetation construction and promote the sustainable socio-economic development. Moreover, the concept of tradeoff index would not only be used in the quantitative analysis of tradeoff between ecosystem services, and also can be used to quantify the degree of synergy between ecosystem services, such as NPP and soil conservation.

5 Conclusions

In this study, a method was proposed to analyze the tradeoff hotspot between ecosystem services. We selected the Yanhe Basin as study area to illustrate the application process and estimated the amounts of NPP and water yield by using biophysical models during 2000–2008. The results of NPP calculation showed that a significant increasing trend emerged in the study period, and shrub is best suited for growing in the Yanhe Basin. For water yield, there is a decreasing trend across the whole basin from 2000–2008, and the disproportionate reduction of annual water yield led to a more seriously unbalanced distribution of water yield in the interior basin. The previous studies and results of correlation analysis indicated that there was tradeoff between NPP and water yield in the study area. Tradeoff index was established and calculated to quantify the extent of tradeoff between NPP and water yield, and the average value of $TI_{\mathrm{NPP/WY}}$ is 24.4 g/(mm·m^2). The tradeoff hotspots was defined as a place of the lowest 20% water yield and lowest 20% $TI_{\mathrm{NPP/WY}}$ within the study area, and the tradeoff hotspots were concentrated in the middle part of the Yanhe Basin and marginal areas of the southern basin. As an example, shrub seems to be a potential influencing factor exacerbating the tension of water shortage from overlapping maps between tradeoff hotspots and land uses. The method of tradeoff index also could be used to quantify the degree of synergy between ecosystem services.

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