Half century change of interactions among ecosystem services driven by ecological restoration: quantification and policy implications at a watershed scale in the Chinese Loess Plateau

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Abstract

The concept of Ecosystem Service (ES) has provided an underpinning framework for ecological restoration research and applications. Ecological restoration is a corrective intervention that aims to reverse land degradation and to contribute to the 2030 Global Sustainable Development goal of Land Degradation Neutrality. It is critical to investigate the long-term effects of ecological restoration and land use change on ESs and ES interactions (synergies or trade-offs) to better understand the mechanisms supporting this goal. This paper describes an analysis of land use and ESs using historical data for a typical watershed in Chinese Loess Plateau, which has experienced series of restoration activities since the 1950s. Six important ESs (food provisioning, soil retention, hydrological regulation, carbon sequestration, water purification and habitat provisioning for biodiversity) were quantified at eight intervals between 1958 and 2015. The interactions between ESs were evaluated by correlation analysis. The results show that soil retention, carbon sequestration, water purification and habitat provisioning for biodiversity increased significantly across the different land use types over several decades but not hydrological regulation. The relationship between ESs were found to be variable over different time periods and a transition point between 1990 and 1995 was identified. Grassland was found to maintain greater water yield than woodland with high values of other ESs. The results suggest that trade-offs between ESs can be mitigated by adjusting the proportion of some important land use types (such as woodland and grassland).

Keywords: land-use change, ecosystem service, ecological restoration, temporal scale,

watershed management, correlation analysis

1. Introduction

Ecosystem services (ESs) are the benefits that people obtain from ecosystems (MA, 2005). Changes in ES are driven by combinations of natural or anthropogenic factors (MA, 2005). The major direct driving forces are generally biophysical factors, including climate change, plant nutrient use, invasive species and plant diseases, while the indirect ones are typically anthropogenic activities (Su et al., 2012a), for example that result in significant land use changes.

Landscape management has to balance the relationship between different ESs, enhancing the synergies and weaken the trade-offs between them (Su et al., 2012a; Tallis et al., 2008; Zheng et al., 2016; Zheng et al., 2014). A trade-off occurs when enhancing one ES directly or indirectly decreases another ES, while a synergy occurs when two or more ESs change in the same direction (Tomscha and Gergel, 2016). Effective landscape management requires an understanding of the relationships between different ESs (Yi et al., 2018) and in what situations trade-offs or synergies would occur (Sun and Li, 2017). Therefore, a trade-off analysis of ESs is a key step in landscape planning, management, and decision making (Darvill and Lindo, 2016; Feng et al., 2017; Jia et al., 2014; Mach et al., 2015). Many studies have quantitatively assessed and discussed the relationships of paired ESs using various methods. Correlation analysis is one of the most commonly used approaches to do this (e.g. Hou et al., 2017; Liu et al., 2019; Su and Fu, 2013; Sun and Li, 2017; Wang et al., 2012; Wu et al., 2013; Xu et al., 2016; Zheng et al., 2016). Jiang et al. (2018) combined correlation analysis and a constraint line approach to measure the complex interactions amongst multiple factors associated with different ESs. Lü et al. (2014) and Feng et al. (2017) used a trade-off index (root mean square deviation) to quantify the trade-offs and synergies among different regulating services.

Land use is a significant factor associated with ES provisioning (Burkhard et al., 2012; Dallimer et al., 2015; Kindu et al., 2016; Li et al., 2010; Liang et al., 2017; MA, 2005; Metzger et al., 2006; Zhao et al., 2006) . It is therefore important to quantify the relationships between land use changes and the changes in ESs as these can support a deeper understanding of the mechanisms associated with the enhancement of any given ES and can provide useful guidance for potential future ecological restoration strategies (Bryan, 2013; Foley et al., 2005; Zheng et al., 2014).

Changing land use through ecological restoration provides a critical corrective intervention for addressing land degradation and contributes to the 2030 Global Sustainable Development goal of Land Degradation Neutrality. The Chinese Loess Plateau has been the subject of several ecological restoration programs and a number of studies have reported the effects of restoration initiatives on ESs in this region. Feng et al. (2013) and Xiao (2014) calculated the changes in carbon sequestration since the Grain for Green program (GFGP), a large scale vegetation restoration program, over a decade using remote sensing techniques and ecosystem modeling. Jia et al. (2014) and Su et al. (2012a) evaluated the changes in multiple ESs in the northern Shaanxi sub-region and quantified the trade-offs and synergies between provisioning and regulating ESs using regression analysis. Pan et al. (2013) established a measure of total ESs and used trade-offs indices to quantify changes in the spatial distribution of multiple ES supply associated with different environmental and land use factors in Jinghe watershed. A common feature of much previous research is the lack of a temporal dimension in the evaluation of ESs interactions, with simple changes in the spatial configuration of ESs being used to infer temporal dynamics (‘space-for-time’ (Tomscha and Gergel, 2016) – see below), or analysis of ES interactions over short time periods.

In land use planning, managers often aim to maximize one or several ESs through landscape management. However, many ESs are not independent of each other and frequently have highly non-linear relationships (Feng et al., 2017; Rodriguez et al., 2006) over different temporal scales. Long-term ESs changes and interactions are rarely studied, especially those across multiple time intervals (Mouchet et al., 2014; Renard et al., 2015; Tomscha and Gergel, 2016). Ignoring long-term trends makes it difficult to derive robust inferences about the impacts of land use changes on the distribution and quality of some ESs (Dallimer et al., 2015; Tomscha and Gergel, 2016). It is therefore important to quantify the long-term impacts of changes in land use patterns and their impacts on the provision, quality and spatial distribution of different ESs. Some studies have sought to incorporate historical perspectives and time series data in their analysis of ES interactions. Tomscha and Gergel (2016) compared ‘space-for-time’ and ‘change-over-time’ approaches. The former uses changes in spatial relationships to infer dynamics over time, while, the latter focuses explicitly on temporal changes. They found that the space-for-time approaches can result in inconsistent characterizations of ES correlations whereas an explicit focus on temporal change using time series data analysis can support a deeper understanding of ES temporal relationships and their dynamics. Dallimer et al. (2015) also identified time-series analysis and improved understanding of historical ES dynamics and interactions as essential for ES management. The need to examine the temporal dimension in detail, over a series of time intervals, is because any evaluation of change may be significantly impacted by one of environment event such as the extreme weather in a particular year (Bennett et al., 2009; Li et al., 2017b). Additionally, changes in the patterns of ES interactions observed at small temporal scales may be hidden at larger ones and the nature of ES interactions may also change as environmental conditions change or in response to new drivers (Renard et al., 2015). Consequently, it is important to examine the temporal variability of ES relations over longer periods, with frequent temporal sampling (Hein et al., 2016; Li et al., 2017b).

The objectives of this paper are: (1) to quantify changes in land use and land cover (LULC) in relation to several important ESs (i.e. food provisioning, soil retention, hydrological regulation, carbon sequestration, water purification and habitat provisioning for biodiversity) in the Zhifanggou watershed in the Chinese Loess Plateau since the 1950s; (2) to identify the relationship between paired ESs under long-term LULC changes ; (3) to discuss the scientific and practical implications of the findings of this study for the comprehensive management of ES and ecological restoration at watershed scale.

2. Research area

The study area, Zhifanggou watershed (latitude 36°46′18″-36°43′13″N, longitude 109°14′01″-109°16′04″E), lies in the middle part of the Chinese Loess Plateau. The total area is about 8.27 km^2 and elevations are 1030-1413m. It is characterized by semi-arid climate and hilly-gully topography with thick loess coverage. The mean annual temperature is 8.8℃, and the mean annual precipitation is 543mm, mainly falling from June to September.

[INSERT FIG. 1 HERE**]**

The Zhifanggou watershed has been experienced a number of environmental events and has been one of the areas selected for ecological restoration projects. For these reasons it was identified as a suitable watershed to investigate the relationships amongst ecological restoration, land use change and ES interactions. The soil of this area is the typical loess soil and susceptible to erosion. Since the late 1930s, the population has increased steadily and ongoing anthropogenic activities have significantly changed the land use pattern and aggravated soil erosion processes (Li et al., 2004). The amount of farmland increased rapidly with little consideration of ecological impacts, resulting in severe soil erosion, landscape degradation and other environmental problems. Consequently, a number of schemes to prevent soil erosion have been initiated over past decades. Since the 1970s, soil and water conservation, comprehensive watershed management and vegetation restoration have all been implemented in this small watershed (Wang et al., 2012; Zhou and Liu, 2009). It was also one of the pilot and demonstration areas for the GFGP which was implemented in 1999.

3. Data and methods

3.1. Data resources

In this study, multi-temporal data were assembled to investigate the LULC changes at intervals during the period 1958 to 2015. Vector based maps of land use were classified through the aerial photograph interpretation (API) at scales of 1:3500, 1:4500, 1:10000 and 1:10000, taken in February 1958, May 1978, June 1990 and June 1995, respectively (Fu et al., 2006). Prior to the API, a land use reconnaissance survey was carried out to obtain a general understanding of the land use situation of the study area (Fu et al., 2006). Other data for 2000, 2005, 2010 and 2015 were generated through interpretation of combined Landsat TM and Google Earth images. The LULC was classified into six categories: farmland, woodland, grassland, water, artificial surfaces and unused land and linked to data on climate, topology and soil type to calculate different ESs. The details and sources of these datasets are listed in Table A.1.

3.2. Estimation of ESs

The following six ESs were calculated for each of the eight time points (1958, 1978, 1990, 1995, 2000, 2005, 2010 and 2015): food provisioning, soil retention, carbon sequestration, hydrological regulation, water purification and habitat provisioning for biodiversity. They were selected because of their relevance to current and future management and decision-making. The following subsections describe how they were calculated.

3.2.1. Food provisioning

Food provisioning is an important type of provisioning service and agricultural production plays a significant role in guaranteeing local incomes, livelihood and economic development. Crop yield (CY) was chosen as the indicator of this service. The data was obtained from existing publications (Zhang et al., 1998; Zhou and Liu, 2009) and the yearbooks of the Yan'an municipality that covers the study area.

3.2.2. Soil retention

In this study, soil retention (SR) was estimated using the Universal Soil Loss Equation (USLE, Renard et al., 1997) as follows:

$$SR = RKLS - USLE = R\times K\times LS - R\times K\times LS\times C\times P = R\times K\times LS\times(1 - C\times P)$$

where SR is the amount of annual soil retention (t ha^{-1} yr^{-1}), a measure of the gap between potential and actual soil erosion; $RKLS$ is the potential soil loss with no vegetation coverage or support practice (t ha^{-1} yr^{-1}); $USLE$ is the annual soil loss (t ha^{-1} yr^{-1}); R is rainfall erosivity, from daily rainfall (MJ mm ha^{-1}) data (Richardson et al., 1983); K describes a soil erodibility factor (t h MJ^{-1} mm^{-1}), set with reference to Fu (2005); LS is a slope length and steepness factor calculated using the method developed by Desmet and Govers (1996) for two-dimension surfaces; *C* is a cover and management factor computed according to the approach described in publications relevant to the Chinese Loess Plateau (Fu et al., 2005; Hu et al., 2014; Li et al., 2014; Liu and Fu, 2016; Pang et al., 2012; Wei et al., 2002). The *C* values for different LULC are shown in Table A.2. *P* is the support practice factor, which corresponds to a slope gradient factor for farmland (P$= 0.2 + 0.03\theta$, where θ is slope (%)) and set to 1 for all other land use types (Fu et al., 2005).

3.2.3. Hydrological regulation

Water is the most sensitive and limited natural resource, especially in semi-arid and arid regions. In this study, the water yield (WY) was chosen as an indicator of hydrological regulation (Jia et al., 2014; Lü et al., 2012; Sharp et al., 2016) as it captures natural irrigation, drainage as well as buffers of extremes in river discharge (de Groot et al., 2002; Li et al., 2017b). WY (mm) was estimated from precipitation and evapotraspiration (ET) using the InVEST model under the assumption that changes in annual soil water storage are negligible in the Chinese Loess Plateau (Hou et al., 2017; Jia et al., 2014; Lü et al., 2015). The input data included average annual precipitation, annual reference evapotranspiration (ET_0), soil depth, a coefficient describing plant evapotranspiration for each LULC (*Kc*), plant available water content, LULC class, root depth and a DEM. The fraction of water stored in the soil profile available to plants was based on soil texture according to Saxton et al. (1986). ET_0 was calculated from the Penman-Monteith equation, *Kc* from the mean Leaf Area Index (LAI) (Allen et al., 1998) from 2000 to 2015 for the three main land use types (farmland, grassland and woodland) and root depth was extracted from Bao (2015).

3.2.4. Carbon sequestration

Carbon sequestration is a key regulating service. It is often represented by net primary productivity (NPP) in the literatures (Jiang et al., 2016; Li et al., 2017b; Lü et al., 2012; Ribaudo et al., 2016). In this study, information on this service was generated from multi-temporal measures of Soil Organic Carbon (SOC). SOC values from 1958 to 1978 were derived from soil survey maps from Shaanxi Province Soil Survey Office. SOC has been sampled directly since the 1990s in the watershed with average values for each LULC class allocated for the period 1990 to 1995 according to existing publications (Chen et al., 2010; Zhang and Chen, 2010; Zheng, 1996). SOC values from 2000 to 2015 were determined according to values given in the literatures (Cao, 2013; Geng et al., 2014; Li et al., 2013; Li, 2013; Liang et al., 2013; Liang, 2011; Liu, 2015; Lü and Liang, 2012; Wang et al., 2002; Xu, 2003; Zhang et al., 2013) and from the spatially distributed NPP values. NPP was estimated using the Carnegie-Ames-Stanford Approach (CASA, Potter et al., 1993), as follows: $NPP = APAR \times \varepsilon$, where NPP is the monthly net primary productivity (gC m^{-2}); $APAR$ is the canopy-absorbed incident solar radiation (MJ m^{-2}), and ε is the light utilization efficiency (gC MJ^{-1}), which is determined by temperature and precipitation.

3.2.5. Habitat provisioning for biodiversity

Biodiversity is closely linked to many ESs. Patterns of biodiversity are inherently spatial and operate over different scales. They can be estimated by analyzing maps of LULC together with land uses that are habitat threats. Habitat quality (HQ) can be used as a proxy for habitat for biodiversity provisioning as it relates to the capacity of ecosystem to provide suitable environments for living organisms (Hou et al., 2017). A HQ index (dimensionless with a relative value 0-1) was calculated using the InVEST model from LULC habitat and biodiversity threat data. The key step is to determine which LULC classes support habitat biodiversity, the sensitivity of these habitats to potential threats (Sharp et al., 2016), the importance or weight of each threat and its persistence across spatial distances. Habitats were classed into woodland, grassland, farmland and water. The threats were framed as LULC transitions to farmland, artificial area and unused land. The threat values were assigned according to the published research (Chen et al., 2016; Du and Rong, 2015; Gao et al., 2016; Jing, 2016; Liu, 2014; Wang, 2016; Xiao, 2011; Zhong and Wang, 2017; Zhu, 2012) and are shown in Table A.2.

3.2.6. Water purification

As well as soil retention and climate (hydrological) regulation, water purification is a crucial regulating service in arid and semi-arid area. Water quality (WQ) was calculated by the InVEST Nutrient Delivery Ratio model to provide an indicator measure of the level of water purification. The model does not capture the detail of the nutrient cycle but rather simulates the long-term, steady-state flow of nutrients through empirical relationships (Sharp et al., 2016). The main parameters are the nitrogen loading and maximum retention efficiency for each land use type, and the distance after which it is assumed that a patch of LULC retains nitrogen at its maximum capacity (Sharp et al., 2016). These empirical parameters were extracted from recent publications (Han et al., 2016; Huang, 2014; Pan, 2016; Wu et al., 2017; Xiao, 2013) and are displayed in Table A.2.

3.3. Trade-off and synergy analysis

3.3.1. Correlation analysis

Correlation analysis and ANOVA were undertaken in this study. ANOVA revealed a significant difference between paired ESs with a significance level of 0.05. Before analyzing ES interaction, a standardized ES (ES_{std}) was calculated for each ES. This seeks to avoid the effects of measurement unit of each ES as follows (Bradford and D'Amato, 2012; Lü et al., 2014):

$$ES_{std} = (ES_{est} - ES_{min})/(ES_{max} - ES_{min})$$

where ES_{est} is the average estimated ES value of each sub-catchment (see below); and ES_{min} and ES_{max} are the minimum and maximum estimated values. The individual ES_{std} ranges from 0 to 1. For water purification, the standardized WQ was calculated using the minimum and maximum nitrogen value in value as ES_{min} and ES_{max} to ensure uniformity in the representativeness across ES_{std} values.

Correlation analysis is often used to determine the relationship between ESs (Su and Fu, 2013; Wu et al., 2013). The Pearson correlation coefficients between each pair of ESs were calculated to provide measures of trade-off (positive values) and synergy (negative values). The Zhifanggou watershed was divided into 40 sub-catchments (Fig. A.1) to accommodate the different spatial scales of processes related to the above mentioned ES indicators. The zonal mean values of each ES indicator for each sub-catchment were calculated (in this case using the Zonal Statistics as Table tool in

ArcGIS 10.2) and standardized to quantify the correlation coefficients. In general, climatic and land use changes were found to be the major drivers of the fluctuations in ESs (Bateman et al., 2013; Fu et al., 2017; Schroter et al., 2005), especially for those related to hydrological regulation and soil retention (Jiang et al., 2016; Pan et al., 2013; Su and Fu, 2013) as they typically vary with rainfall (Fig. A.2), which may conceal the influence of any LULC change. Thus mean annual rainfall (543mm) was considered to be uniform across such a small watershed and used as an input to calculate these ES indicators and to capture the impacts of land use changes on ESs. The Pearson correlation coefficients between pairs of ESs were calculated using SPSS 22.0.

3.3.2. Root mean square deviation

Root mean square deviation (RMSD) was used to quantify the trade-offs among two or more ESs as in Bradford and D'Amato (2012).

$$\mathrm{RMSD} = \sqrt{\frac{1}{n-1} \times \sum_{i}^{n} (ES_i - \overline{ES})^2}$$

where ES_i is the standardized value of *ES i*, and $\overline{ES}$ is the expected value of the *i* number *ES*. In brief, it extends the meaning of trade-off from negatively correlated relationships to the inclusion of uneven rates of same-direction change between ESs (Lü et al., 2014). In other words, even when a synergistic relationship between the two ESs is present, it may be tendentious with the effect that an increment of one service is likely to an uneven increase in the other. It is a simple but effective way to represent the degrees of trade-offs between any two or more ESs, no matter how they are correlated to each other (Lü et al., 2014). This measure also supports decisions and choices over more suitable synergistic LULC types (i.e. with smaller RMSD values). More details and illustrations of the trade-offs between two ESs through RMSD is provided in Bradford and D'Amato (2012) and Lü et al. (2014).

4. Results and discussions

4.1. Policy-driven vegetation restoration and associated land use change is the major driver for ES change

4.1.1 Land use and land cover under policies implement

The percentage of each LULC class in different periods is shown in Fig. 2(a). In 1958, the main LULC classes were grassland and farmland, which accounted for 31.78% and 56.34% of the watershed, respectively. In 2015, woodland, grassland and farmland accounted for 52.43%, 36.31% and 10% of the watershed, respectively. The main land use changes over the past half century, therefore, were significantly increased woodland and reduced farmland. Another LULC change was the decrease in unused land from 10.63% to 0%. There are some slight fluctuations in grassland around a stable level. Little variation can be seen in water and artificial surfaces (both within 0.5%).

[INSERT FIG. 2 HERE**]**

The LULC transfer matrix in Table A.3 indicates that the changes in LULC were not simply transitions from farmland and unused land to woodland. The main LULC conversions were from farmland to woodland (54.05% of the 1958 area) and grassland (30.62%), from grassland to woodland (54.88%), from artificial surfaces to woodland (28.94%) and from unused land to woodland (54.97%) and grassland (39.17%). The locations of these overall changes are shown in Fig. A.3.

It is important to consider when these changes occurred. The three main land use types, farmland, grassland and woodland, were analyzed further and Fig. 2. (b, c and d) shows the percentage changes (%) of these over the different time intervals. Farmland decreased continually over the 6 decades, with the two largest reduction periods between 1978-1990 and 1995-2000 (12.6% and 25.1%, respectively). Conversely, woodland maintained an increasing trend from 1958 to 2015, with the two largest increases during the same two periods (18.3% and 19.9%, respectively). According to the history of this watershed, these two periods witnessed two important ecological restoration projects (comprehensive watershed management and GFGP). The amount of grassland was not completely stable with small fluctuations around from -4% to 6% across the whole period due to transitions from unused land and the transition to woodland (Table A.3). Its location changed considerably (Fig. A.3) indicating the significant changes in this class.

4.1.2. Variations of ecosystem services

Based on the above methods (Section 3.2), values for each ES indicator were calculated (see Table A.4) and standardized ES indicators are shown in the radar graphs (Fig. 3) for each of the eight time periods. The values of several ES indicators, CY, SR, HQ and WQ, increased continually over the whole period, peaking around 2000. SOC decreased initially (1958 - 1990) and then increased to 2015. Conversely, there was a downward trend in the WY over study period. The radar graphs show that changes in these mainly happened during 1978-2000 corresponding to the observed LULC changes. Many of the ES indicators improved through land use changes driven by ecological restoration projects, but the increased water use associated with vegetation restoration resulted in a significant decrease on water yield.

[INSERT FIG. 3 HERE**]**

4.1.3. The major driver is the policy rather than climate change

Changes in climate and policy are two important factors that influence the ES provisioning. The trends and changes of the two main climatic variables, precipitation and temperature, during the last half century are shown in Fig. 4. Annual average rainfall showed a non-significant negative trend (slope=-0.467, R^2=0.0049, P=0.58). Mean annual rainfall was used to calculate WY and SR with the implication that precipitation has little influence on the results. Fig. 4 shows that there is a significant positive trend for annual average temperature (slope=0.033, R^2=0.589, P=8.66×10^{-14}). Temperature is one factor for reference evapotranspiration in WY. Using the climatic factors of 1958, water yield was calculated under different LULC scenarios (1978-2015) to evaluate their contribution to this ES (Fig. 5). Land use change makes an important contribution to decreasing WY and its effects are greater than climatic factors under uniform rainfall, especially after ecological restoration. Thus temperature is not a key factor associated with ES change.

[INSERT FIG. 4 HERE**]**

[INSERT FIG. 5 HERE**]**

There is an obvious chain of policy implementation, leading to land use change, leading to ES changes. The Zhifanggou watershed witnessed a series of significant historical events. Before the 1930s few people lived in the area and the population has increased steadily since then (Fu et al., 2006; Zhang et al., 2004). In the 1950s, policy encouraged farming and the felling and clearing of natural vegetation for fuel. At that time individuals were less aware of and concerned with the regulating and supporting environmental protection services in their pursuit of provisioning services such as food and fuel. Because of rapid population growth and low yields, more and more land was used to produce grain and natural vegetation was destroyed, leading to increased and severe soil erosion. This reduced land fertility and more land had to be converted to agriculture from natural vegetation to sustain population growth. Thus during this period the land use structure in the watershed was subject to a number of pressures. To alleviate this and to increase net grain yields and to reduce the pressure on farming, policy at the national level distributed land use rights to individual farmers through the introduction of the Household Responsibility System and controlled population growth by implementation of the Family Planning Policy in 1978. In the early 1980s, the Chinese government initiated watershed soil and water conservation programs by constructing terraces and check-dams or by planting non-agricultural vegetation on steep slopes (Fu et al., 2006; Su et al., 2012a; Zhang et al., 2004). Zhifanggou experienced large changes in LULC and associated ESs with the increases of woodland and decreases of farmland. The GFGP is the largest ecological restoration program in China and the Zhifanggou watershed was part of the pilot project during the first phase of the GFGP in 1999 (Hou et al., 2017; Lü et al., 2015). This explains the increase in woodland from 1978 to 1990 and from 1995 to 2000.

The results of this study show several major changes in ESs after vegetation restoration policies. Although the area of farmland shrunk significantly after 1978, food provisioning is influenced by not only cropland area but also technological and economic developments, which increased yields and the diversity of grain species. For hydrological regulation, dramatic decreases occurred after two phases of ecological restoration, mainly associated with increases in woodland which increases evapotranspiration and leads to water shortages (Jackson et al., 2005; Li et al., 2017b). However, water yield is an important resource, supporting ecosystem functioning, human life and agricultural production (Zheng et al., 2016). Understanding this balance between different water related ESs has been a critical development in recent research. Feng et al. (2016) noted that the Loess Plateau is approaching its sustainable water resource threshold when the demands from vegetation restoration and human society are considered. Additionally, since different LULC types support distinctive ESs, both water purification and habitat quality were found to increase dramatically after the implementation of ecological restoration programs. This reinforces the functional chain of "policy implementation-land use change-ES change". Similar chains have also been observed in studies in other countries (e.g., Arunyawat and Shrestha, 2016).

4.2. Grassland is a more suitable for ecological restoration in drylands

In order to understand the temporal variation in ESs, the percentage change for each ES indicator was calculated for each of the 7 time intervals (Fig. 6). Two periods, 1978-1990 and 1995-2005, witnessed a significant increase in food provisioning and a decrease in farmland area. Although the area of cultivated land decreased, the unit area grain yield increased significantly. Carbon sequestration fluctuated greatly during the whole period showing a decline at first and then large increases. There are three points deserving more attention. Firstly, soil retention increased continuously from 1958 to 2000 but the degree of increment remained almost even. That is to say, increased woodland under the implementation of ecological restoration (comprehensive watershed management and GFGP) didn't dramatically increase soil retention. Secondly, a general decreasing trend can be seen for water yield over the whole period, especially after the GFGP (1995-2000). Finally, the improvements of HQ and WQ mainly occurred during the periods of 1978-1990 and 1995-2000, which were the main periods for woodland increment. However, the increases in HQ after

GFGP (1995-2000) were not so obvious as over the period 1978-1990, indicating that woodland may be not the most important factor for maintaining habitat quality.

[INSERT FIG. 6 HERE**]**

To further investigate these findings, root mean square deviation (RMSD) of paired ESs in different land use types was used to better understand the changes in ES trade-offs (Fig. 7). Overall, the RMSDs among all paired services (except for HQ-WQ) are lower for grassland than for woodland. This indicates that the ESs provided by woodland may be more tendentious and uneven. Grassland acts as a recovery measure with much smaller RMSD and therefore may support a greater level of synergistic ESs. Similar findings have been noted by other studies in the Loess Plateau (Li et al., 2017b; Pan et al., 2013).

[INSERT FIG. 7 HERE**]**

4.3. Long-term monitoring and assessment are critical for understanding the variability of complex ESs interactions

4.3.1. Changes in relationships between paired ESs

History can provide a mirror into the future to understand the potential impacts of future change under different scenarios. Here coefficients were calculated for the correlations between spatial patterns and between temporal dynamics (Zheng et al.,

2014) over the 40 sub-catchments. The coefficients of the spatial distribution of two ESs were derived from environmental gradients, spatial patterns of vegetation or LULC. They reflect a static correspondence relationship with positive values indicating that the spatial distributions of both ESs are consistent (both ESs display a higher or lower value at the same time) (Zheng et al., 2014). The correlation coefficient for multiple temporal intervals over a long period characterize the dynamic interaction between ESs and the relationships between them and LULC.

The spatial correlation coefficients between of each ES indicator at each period in time for the 40 sub-catchments, capturing ES spatial relationships, are shown in Table 1. Considerable differences can be seen in most ES indicator pairs with some showing contrasting trends across the time period (i.e. between the initial and final time periods). For example, spatial coherence (i.e. synergy) can be observed in SR-WY and WY-HQ before the 1990s with the trade-offs observed after that period, while SOC-HQ and SR-SOC showed the inverse pattern over the same period.

[INSERT TABLE 1 HERE**]**

The temporal correlation coefficients for each pair of ES indicators are listed in Table 2. These were calculated over the 40 sub-catchments (under the average rainfall) over paired time intervals. Positive values indicate that the two ES indicators changed in the same direction and that a synergy may exist between them, and negative values infer a trade-off (Zheng et al., 2014). Over the past half century some pairs of ES indictors, such as SR-WY, WY-SOC, WY-HQ and WY-WQ showed varying directional trends and degrees of correlation. Another surprising trend is that all coefficients were positive from 1990 to 1995, regardless of relationship was before or after the period.

[INSERT TABLE 2 HERE**]**

4.3.2. Long-term monitoring and assessment are basic and critical tools

Long-term data provide the temporal perspective needed to identify the underlying thresholds of ES change on for future planning. The spatial and temporal interactions among paired ESs reveal that interactions are not temporally fixed. This highlights the need to consider the temporal dynamics of ESs and their drivers over long periods to better understand the trade-offs and synergies among multiple ESs, especially during ecological restoration activities (Li et al., 2017a). Both spatial and temporal correlation analysis of the 40 sub-catchments over 8 time periods in this research identified major changes in relationships between pairs of ESs before 1990 and after 1995. Greater temporal synergies were found between 1990 and 1995 with positive values of ES indicators (Table 2). Considering these findings alongside those from previous research (Li et al., 2017b; Pan et al., 2013) and the area of each LULC at that period (Section 4.1.1), a ratio of grassland to woodland of around 1.5 for the Zhifanggou watershed could support more synergies between ESs. Of course, it is important to guarantee both food yield and security and to ensure suitable locations for different LULC types. However, if this finding is correct then low ES indicator values can be improved in other ways. For example, WQ and CY could be increased with advanced agricultural technology and SOC could be accumulated with the growth and soil retention of vegetation. The ratio, therefore, is an important reference for future research in similar watersheds in the Loess Plateau and other arid and semi-arid areas. Assessment of long-term data provides the basis for identifying the dynamics of ES interactions and to suggest future planning strategies to achieve this ratio.

Due to the lack of historical data, many previous studies (Qiu and Turner, 2013; Raudsepp-Hearne et al., 2010; Tomscha and Gergel, 2016) have used space-for-time substitution to explore the relationship between ESs. Such methods, however, make two assumptions (Tomscha and Gergel, 2016): (1) that temporal and spatial variability are equal; (2) that historical drivers operate evenly. Recent studies have shown that landscape history, especially evaluations of multiple time intervals, can play a critical role in modeling ESs and their interactions over time (Dallimer et al., 2015; Renard et al., 2015). Research often seeks to identify immediate gains in ES synergies to support planning and management, but ignores the long-term trade-offs. The importance of long-term monitoring relates to the need to sufficiently capture complex long-term ES interactions, which can more deeply inform strategies to simultaneously avoid or minimize trade-offs (Tomscha and Gergel, 2016).

The fifteenth of the seventeen goals for sustainable development presented by the United Nations refers to achieving a land degradation-neutral world by 2030. In order to achieve this goal, monitoring land status is a fundamental and key component (Grainger, 2015; Sietz et al., 2017; Tal, 2015) of any analysis which should also include multiple indicators such as soil properties (Toth et al., 2018) and land productivity (Cowie et al., 2018). Changes in LULC, ESs and their relationships should be monitored and assessed over long periods in order to support the development and iterative refinement of land use planning and management. Renard et al. (2015) and Tomscha and Gergel (2016) also suggested that the ES relationships should be recognized and included as part of long-term monitoring of ESs. A long-term national or even global network of monitoring should be encouraged (Luo et.al, 2018; Safriel, 2017) to monitor potential land degradation over time and its impacts on ESs to inform management activities (Renard et al., 2015).

4.4. Limitation from data sources and models

Data quality, availability, completeness and uniformity is a big challenge for analysing of ESs over long periods. Non-uniform historical data may make data comparisons and integration difficult (Dallimer et al., 2015; Hein et al., 2016; Raudsepp-Hearne et al., 2010) because of the uncertainty involved. For example, the SOC was estimated only for surface soil depths (20 cm), underestimating any SOC in deeper soil layers.

The identification and classification of LULC are also possible sources of uncertainty. The broad categories used to interpret the remote sensing image will result in the loss of potentially important information. For example, if all woodlands are regarded as one LULC class, coarse estimates on soil retention, water penetration and evapotranspiration, or NPP may be expected if the impacts of some detailed features such as forest age, forest canopy coverage, and species composition are not considered. Inevitably the degree of detail is limited by the source data and the comparatively long temporal scale in the present research.

Uncertainties are also present in the assessment of ES indicators using models. Firstly, several factors affect the accuracy of annual WY estimates. Although the results of evapotranspiration modeling were considered to be much closer to reality than the results obtained from the remote sensing based product (MODIS-ET), other uncertainties also arise (Lü et al., 2012): (1) changes in water storage should not be negligible for wet years; (2) water resources are used by communities and are affected by soil conservation structures (e.g., check dams); and (3) there will be differences in water demand for vegetation with different species and in restoration years. Secondly, the estimation of SR was undertaken through the application of the USLE, which is based on a statistical relationship established from a large number of plot scale rainfall-erosion experiments (Ciesiolka et al., 2006; Kinnell, 2008). It estimates rill and interrill soil detachments on hill slopes from rainfall, soil and soil cover parameters, and management factors (Tattari and Barlund, 2001). Therefore, it is a suitable method to estimate the effect of hill slope vegetation rehabilitation on soil conservation. However, this may have been overestimated in this research due to the omission of the local sediment deposition process (Kinnell, 2008) and the use of degraded bare ground as control (Zhang et al., 2017). These overestimations were made for the absolute values of annual SR but did not exclude the SR brought by vegetation rehabilitation. Uncertainties also arose in the estimation of input parameters for the USLE (Tattari and Barlund, 2001). To reduce this, parameters experimentally established and verified in the Loess Plateau region were used for estimating the different factors in the USLE (Fu et al., 2011; Liu and Fu, 2016; Lü et al., 2012; Su and Fu, 2013; Su et al., 2012b). Similarly, uncertainty reduction in modeling HQ and WQ was through using experiential parameters reported for the Chinese Loess Plateau as much as possible.

5. Conclusions

Quantifying ESs and their relationships is critical for ecosystem management, landscape sustainability and to achieve the UN land degradation-neutral goal. Quantitative evaluation of historical land use changes and the ecosystem services dynamics they support, allows ES synergies and trade-offs to be robustly identified, especially those related to ecological restoration.

This paper analyzed the change in LULC, the provision of ESs and their interactions in a typical small watershed in the Chinese Loess Plateau over a period of half a century using models and correlation analysis. Habitat quality, soil retention, water purification and habitat provisioning for biodiversity were found to have increased significantly over the last decades under a series of national policies, while, hydrological regulation decreased significantly. Grassland was suggested to be more suitable for ecological restoration in the semi-arid region than previously thought as it was able to maintain greater water yield than woodland with high levels of other ESs.

Large differences in the relationships between ESs were detected before and after a transition period from 1990 to 1995). A possible optimum ratio between grassland and woodland (about 1.5) during this period may support greater levels of synergistic ESs. The long-term monitoring for dynamics of ES indicators at watershed scale deserves more attention to support informed land management. This study advances and enhances a wider understanding of ESs and their interactions, as mediated by land use change and ecological restoration activities. This supports actions towards the UN Land Degradation Neutrality goal.

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Appendices

There are three pictures and four tables as appendices in supplementary materials.

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Lists of Figs. 1-7:

Fig. 1 Location and photos of Zhifanggou watershed.

Fig. 2 a: percentage area (%) for each type of LULC at eight periods; b, c and d: changes in area percentage (%) for farmland, woodland and grassland, respectively.

Fig. 3 Radar graph of the standardized ES indicators for each time period between 1958 and 2015.

Fig. 4 Time series of (a) annual precipitation and (b) mean annual temperature during 1951-2015.

Fig. 5 The effect of LULC and climatic factors on water yield.

Fig. 6 Percentage changes of ES indicators over each paired time period.

Fig. 7 The values of RMSD between each two ES indicators for the whole period

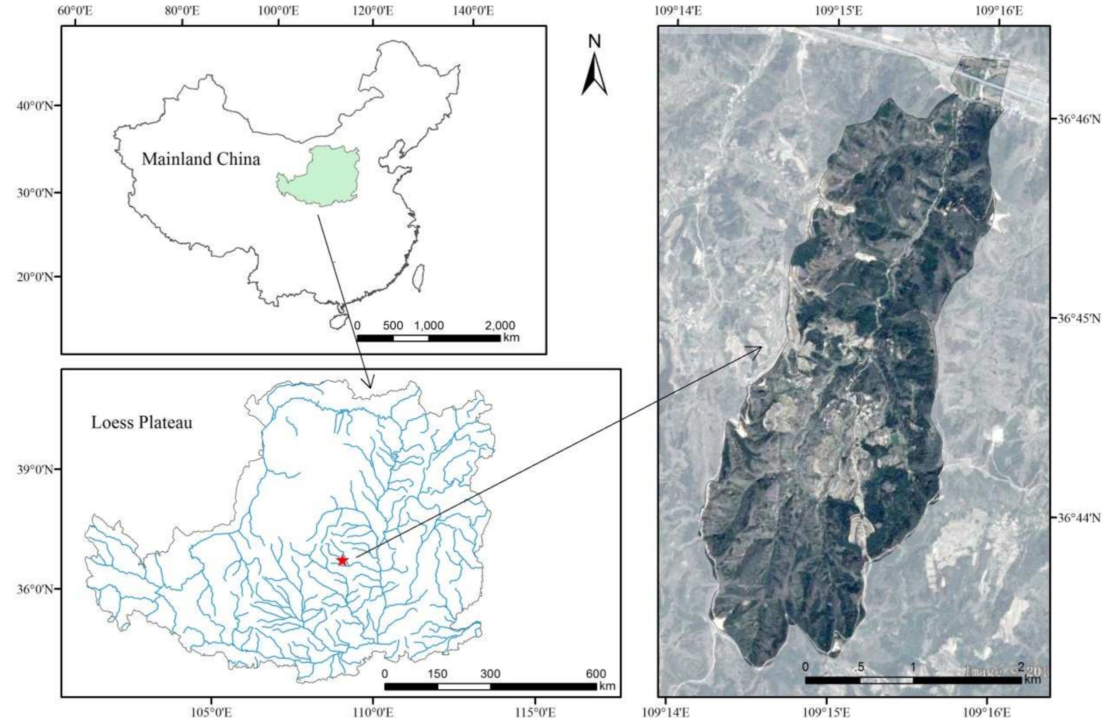

Fig. 1. Location and photos of Zhifanggou watershed. a: the location of Zhifanggou watershed in Chinese Loess Plateau with a Google Earth image of the study area on the 25th of July, 2015. b: three photos taken during a field survey of the watershed in May of 2017.

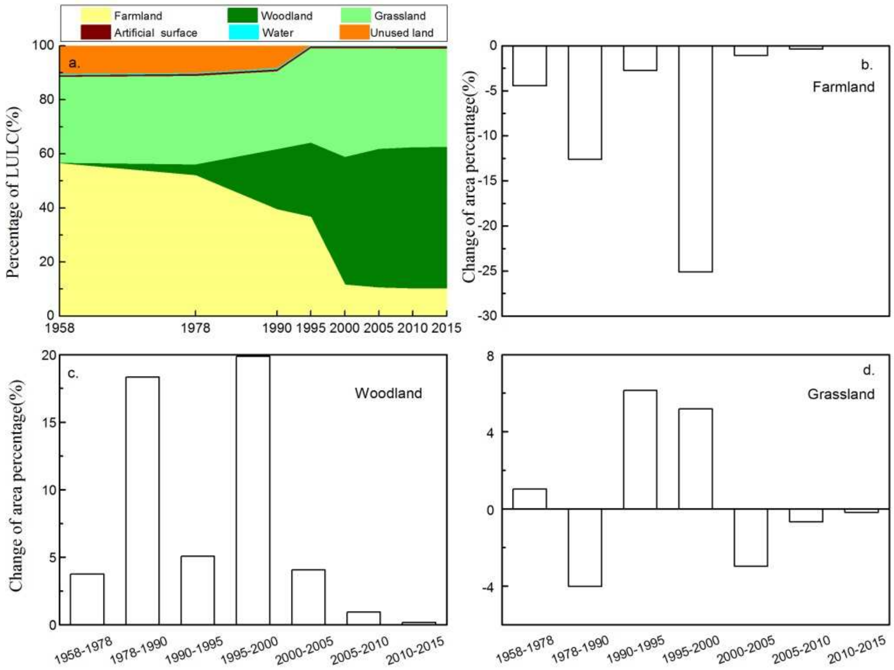

Fig. 2. a: percentage area (%) for each type of LULC at eight periods; b, c and d: changes in area percentage (%) for farmland, woodland and grassland, respectively.

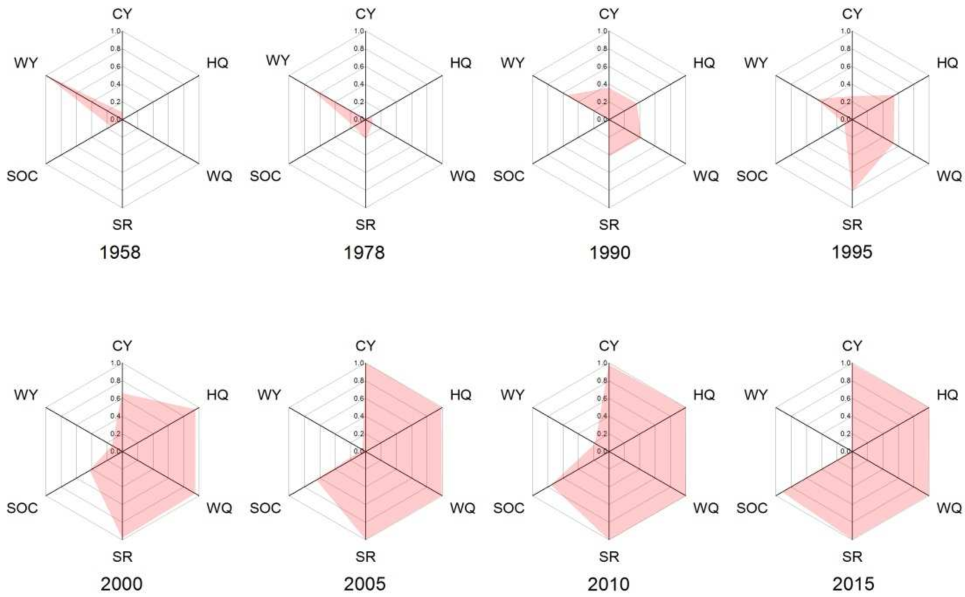

Fig. 3. Radar graph of the standardized ES indicators for each time period between 1958 and 2015. CY is crop yield, SR is soil retention, WY is water yield, SOC is soil organic carbon, HQ is habitat quality and WQ is water quality.

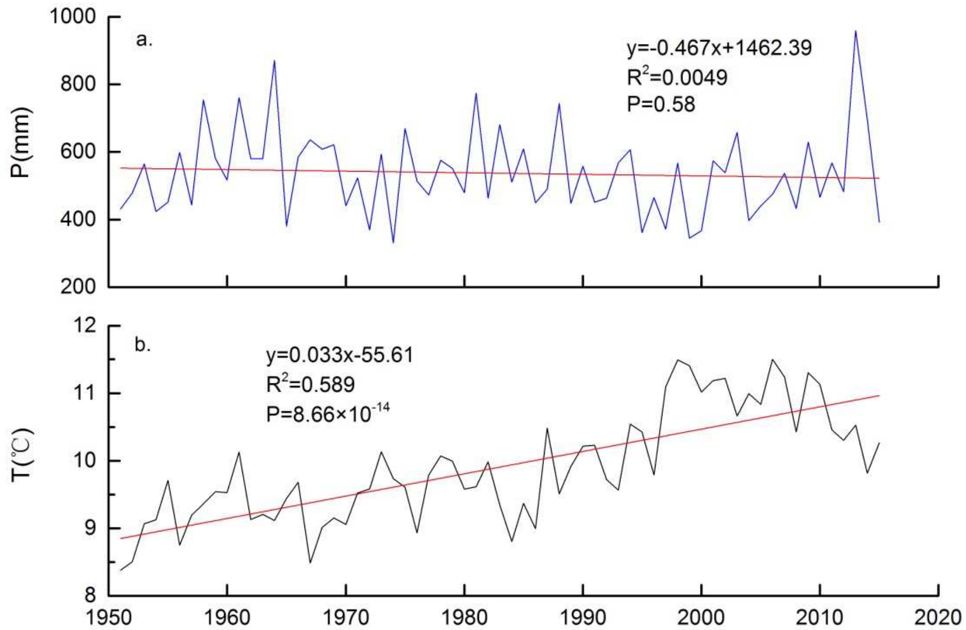

Fig. 4. Time series of (a) annual precipitation and (b) mean annual temperature during 1951-2015.

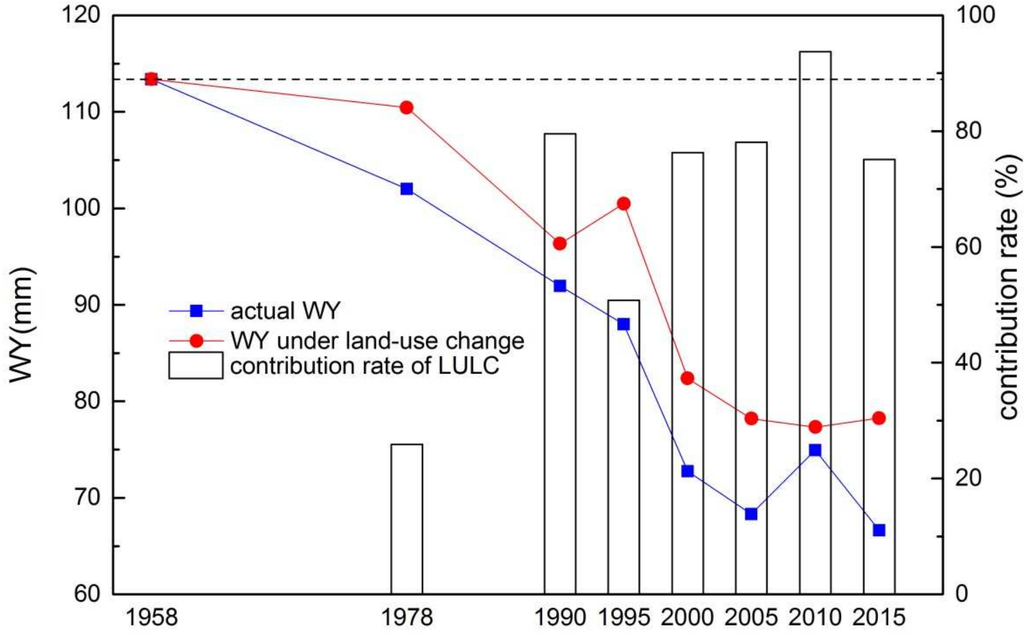

Fig. 5. The effect of LULC and climatic factors on water yield. The change of water yield (WY) driven by LULC (red line) and by both LULC and other climatic factors under average annual precipitation (543mm) (blue line), with the contribution of LULC shown by the bar on decreased WY. The gap between red and dotted line is the effect of LULC on WY, and the gap between the blue and dotted lines is the effect of both LULC and climatic factors.

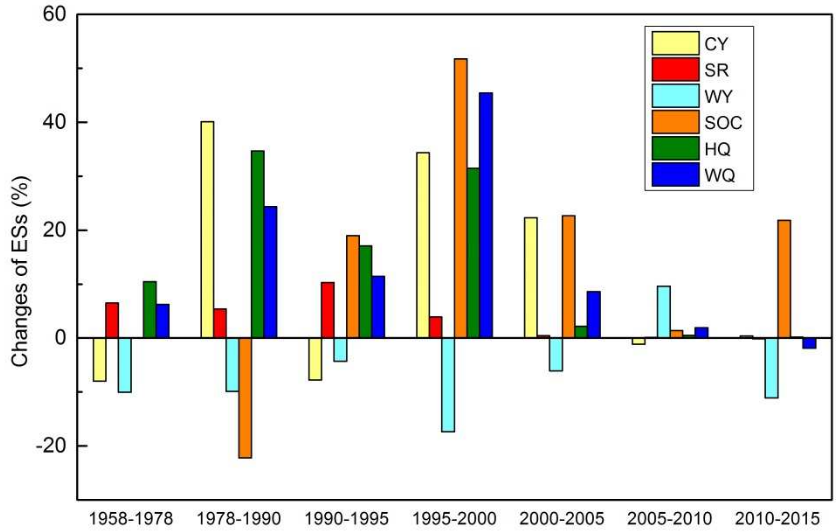

Fig. 6. Percentage changes of ES indicators over each paired time period. CY is crop yield, SR is soil retention, WY is water yield, SOC is soil organic carbon, HQ is habitat quality and WQ is water quality.

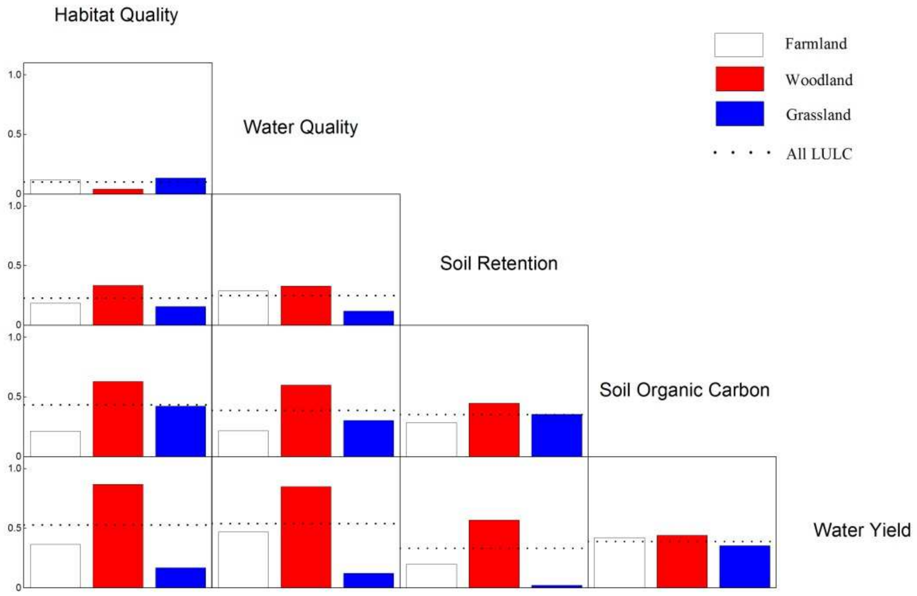

Fig. 7. The values of RMSD between each two ES indicators for the whole period

Lists of Tables 1-2:

Table 1 The spatial correlation of paired ES indicators for each period

	1958	1978	1990	1995	2000	2005	2010	2015
SR-WY	0.605**	0.528**	0.106	-0.299	-0.299	-0.374*	-0.386*	-0.425**
SR-SOC	-0.623**	-0.603**	0.555**	0.394*	0.394*	0.644**	0.514**	0.393*
SR-HQ	0.643**	0.491**	0.404**	0.282	0.480**	0.540**	0.528**	0.522**
SR-WQ	-0.107	-0.071	-0.062	0.214	0.435**	0.480**	0.470**	0.472**
WY-SOC	-0.805**	-0.785**	-0.478**	-0.961**	-0.583**	-0.415**	-0.551**	-0.421**
WY-HQ	0.467**	0.063	-0.588**	-0.891**	-0.806**	-0.816**	-0.820**	-0.831**
WY-WQ	-0.073	-0.376*	-0.692**	-0.758**	-0.726**	-0.789**	-0.794**	-0.777**
SOC-HQ	-0.731**	-0.451**	0.922**	0.918**	0.435**	0.733**	0.773**	0.673**
SOC-WQ	-0.044	0.062	0.583**	0.753**	0.358*	0.674**	0.689**	0.600**
HQ-WQ	0.217	0.466**	0.741**	0.84**	0.920**	0.931**	0.929**	0.937**

Blue and red numbers represent significantly positive and negative correlations, respectively (* indicates $p < 0.05$; ** $p < 0.01$; No * $p \geq 0.05$). CY is crop yield, SR is soil retention, WY is water yield, SOC is soil organic carbon, HQ is habitat quality and WQ is water quality.

Table 2 The temporal correlation of paired ES indicators during each two periods

	1958-1978	1978-1990	1990-1995	1995-2000	2000-2005	2005-2010	2010-2015
SR-WY	-0.526**	-0.402*	0.751**	-0.336*	-0.885**	-0.849**	-0.093
SR-SOC	-	0.195	0.903**	-0.007	0.214	0.128	0.365*
SR-HQ	0.747**	0.713**	0.872**	0.537**	0.787**	0.769**	-0.214
SR-WQ	0.795**	0.706**	0.576**	0.413**	0.552**	0.729**	0.194
WY-SOC	-	-0.554**	0.697**	-0.392*	-0.118	-0.114	-0.313*
WY-HQ	-0.720**	-0.707**	0.647**	-0.841**	-0.797**	-0.806**	-0.22
WY-WQ	-0.722**	-0.75**	0.081	-0.694**	-0.489**	-0.738**	-0.112
SOC-HQ	-	0.44**	0.957**	0.353*	0.233	0.287	-0.04
SOC-WQ	-	0.456**	0.675**	0.287	0.193	0.211	-0.008
HQ-WQ	0.943**	0.917**	0.730**	0.852**	0.518**	0.958**	-0.083

Blue and red numbers represent significantly positive and negative correlations, respectively (* indicates $p < 0.05$; ** $p < 0.01$). CY is crop yield, SR is soil retention, WY is water yield, SOC is soil organic carbon, HQ is habitat quality and WQ is water quality.