# Balancing trade-offs of ecosystem services for improved ecological restoration: a case study in the Loess Plateau of China

***Abbreviations***: SEC: soil erosion control, TC: carbon sequestration, WY: water yield, ForL: forest land, ShrL: shrub land, GraL: grassland, FarL: farmland, ConL: construction land, WatB: water body, VegC: vegetation cover rate, Raif: rainfall amount, $ET_0$: potential evapotranspiration, Alti: altitude, SloG: slope gradients, SOM: soil organic matter content, Clay, Silt, and Sand represent the clay (<0.002 mm), silt (0.002-0.02 mm), and sand (>0.02 mm) contents, respectively.

**Abstract:** Balancing trade-offs among multiple ecosystem services (ESs) is critical for restored ecosystem, including the Loess Plateau of China where ESs are undergoing significant changes. In this study, the ESs in Ansai watershed were quantified and analyzed for the period 2000 to 2014 using high-resolution and site-specific models. Regression and redundancy analysis were applied to unravel the effects of key drivers on changes in ESs from land use, environmental, and morphological factors and their trade-offs. Results show that soil conservation (SEC) and carbon sequestration (TC) increased by about 20% and 82%, while water yield (WY) declined by 38%. Forest and shrub land are shared drivers of changes in ES, and slope gradient, grassland and construction land were independent drivers. Two major trade-offs were identified, the SEC-WY and TC-WY. Slope gradient and grassland had a dominant influence on the SEC-WY trade-off. Quadratic function relationship is found between slope gradient and this trade-off, which is reduced from declines in forest areas and expanding grassland. Regarding the TC-WY tradeoff, there is a unidirectional interaction, and rRainfall, grassland, farmland, and forest land are shared drivers. Rainfall and forest aggravated the trade-off, grassland restrained it, and construction land is an independent driver. The forest and grassland proportion are the dominant drivers affecting the TC-WY trade-off, and quadratic function relationship is also found between these drivers and the trade-

off. Overall, forest and grassland proportions need to be controlled at 20-30% and 45-60%, respectively for…. We proposed the mode of ecological restoration, through which the forest patches with more edges can be set to the contiguous grassland matrix,

**Keywords**: ecosystem services trade-off; soil conservation; carbon storage; water yield; drivers

# 1. Introduction

Ecosystem services (ESs) are indispensable benefits provided by natural ecosystems to humankind, tightening the natural ecosystems and the human society together (MA, 2005; Wu, 2013). While there are high expectations for maximization of several ESs at the same time, these services are sometimes under pressure by non-linear relationships from anthropogenic and environmental disturbances, resulting in unintentional trade-offs (Rodriguez et al., 2006). Analysis of these trade-offs, which are defined as situations where one ES may increase at the cost of another (Bennett et al., 2009; Raudsepp-Hearne et al., 2010), can be an effective method to understand and balance multiple ESs. Thus, trade-off analysis is a key asset for the integration of ESs in land-use planning and decision-making processes (Darvill and Lindo, 2016; Gissi et al., 2016; Wang et al., 2017; Wu et al., 2017).

On Loess Plateau in northwest China, multiple trade-offs among ecosystem services are at play. As the largest and deepest loess deposit in the world, Loess Plateau has long been undergone the severest soil erosion on Earth (Fu et al., 2017). Soil erosion control (SEC) is thus a fundamental ES to ensure ecological safety and agricultural sustainability on Loess Plateau. Following the implementation of the Grain-for-Green Program (GFGP) in 1999 aimed to improve SEC (Chen et al., 2010), the steep croplands on Loess Plateau were converted to forested lands and grasslands. Ten years after the implementation of the GFGP, vegetation coverage on Loess Plateau expanded significantly (Lu et al., 2012). The soil erosion rate decreased from 3362 t/(km$^2$•a) in 2000 to 2405 t/(km$^2$•a) in 2008 (Fu et al., 2011), and the net primary productivity (NPP), an indicator of carbon sequestration (TC) capacity relevant for several fundamental ESs, steadily increased (Feng et al., 2012).

Despite these overall ecological beneficial effects , the GFGP also had negative effects, of which the most important is that the restoration of vegetation coverage led to increasing water consumption and intensifying water shortage problems. The introduced plants tend to consume more water than the native species (Yang et al., 2014), and they rapidly deplete soil water resources and increase the formation of dry soil layer. The dried soil layer can prevent water interchange between the upper soil layer and the groundwater, negatively affecting water cycle (Li and Huang, 2008; Wang et al., 2013). Thus, vegetation restoration may fail because of reduced soil moisture, resulting in even lower biomass accumulation or stunted growth (the little old man trees) (Wang et al., 2008). Dried soils can also enhance water infiltration and reduce runoff (Feng et al., 2015). For example, decreased runoff in the order of 2-37 mm/year was observed in more than half of the Loess Plateau from 2002 to 2008 (Lü et al., 2012), and the total amount of water yield declined by 12% in the Yanhe watershed (at the center of Loess Plateau) from 2000 to 2015, significantly affecting local and downstream water supply (Wu et al., 2018).

Water shortage caused by restoration of vegetation coverage is a serious threat to local vegetation growth and regional water resources security. If this negative trend in vegetation-driven water shortages continues, the achievements in terms of soil conservation and TC are likely to be lost (Feng et al., 2017a). The lack of water resources is an urgent ecological environment problem on Loess Plateau. Understanding and managing the relationships among SEC, TC, and WY under current hydrological conditions, as well as the associated trade-offs and their regulating dominant driving factors, clearly emerges as a main research priority to guide land use planning and mitigation response options. Trade-off analysis has been used in many fields to guide decision making (Darvill and Lindo, 2016; Gissi et al., 2016; Wang et al., 2017; Wu et al., 2018). Previous studies on trade-offs of ESs on Loess Plateau mainly focused on qualitative identification of relationships of ESs (Jia et al., 2014; Lu et al., 2014; Zheng et al., 2014), influencing factors for trade-off (Zheng et al., 2014; Feng et al., 2017a; Hou et al., 2017; Li et al., 2017), hotspot identification of trade-offs (Zheng et al., 2016), designing spatial assessment and optimization models for ESs (Hu et al., 2014), and land use optimization based on trade-offs of ESs (Wu et al., 2018). These studies generally conclude that vegetation restoration in arid areas enhanced conflicts among ESs and excessive water consumption. Minimizing the trade-offs among ESs by better management of vegetation restoration is both a theoretical problem and a practical problem that requires immediate attentions and actions. However, the mechanisms driving ESs trade-offs have not been fully clarified yet, and the current knowledge is insufficient to balance various ESs properly and identify win-win interventions.

The interaction between humankind and nature is most obvious at the moderate scale, which is the more actionable scale in policy making toward a sustainable vegetation restoration (Fang et al., 2015; Fang et al., 2016). In this study, the model InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is used to assess and compare water yields, soil erosion controls, and carbon sequestrations between 2000 and 2014 in Ansai watershed, a typical moderate scale area. Using the theory proposed by Bennett et al. (2009) on impact types of drivers on multiple ESs, we studied trade-offs of ESs in Ansai watershed to achieve better ecological restoration. The specific objectives of the analysis were to (1) determine dominant drivers on individual ES with identification of both shared and independent drivers; (2) explore the mechanisms affecting the trade-offs of ESs and determine threshold value of responses of these trade-offs to their drivers; (3) achieve results that can be used for practical recommendations on land-use planning and vegetation restoration management in the Loess Plateau.

# 2. Methods

## 2.1. Study area

The Yanhe watershed is located at the center of Loess Plateau in China, and the sub-watershed in its upstream section is controlled by Ansai hydrometric station (109°19′ E, 36°52′ N). This sub-watershed is hereby referred to as Ansai watershed (108°47′-109°25′ E, 36°52′-37°19′ N) for the sake of convenience (Figure 1). Ansai watershed covers an area of 1334 $km^2$ in the semiarid temperate zone on northwest China and is characterized by a continental monsoon climate with distinct wet and dry seasons. The soil type in this area is classified as aeolian loess, which has low fertility and is vulnerable to soil erosion. The watershed lies on a warm forest steppe where natural vegetation was destroyed in the past and numerous patches of artificial vegetation were planted by the GFGP. The artificial tree and shrub plantations are mainly composed of *Robinia pseudoacacia*, *Hippophae rhamnoides*, and *Caragana korshinskii.* The grassland is mainly composed of *Stipa bungeana, Artemisia gmelinii*, and *Lespedeza davurica*. The cultivated crops are predominantly maize, millet and broom corn millet.

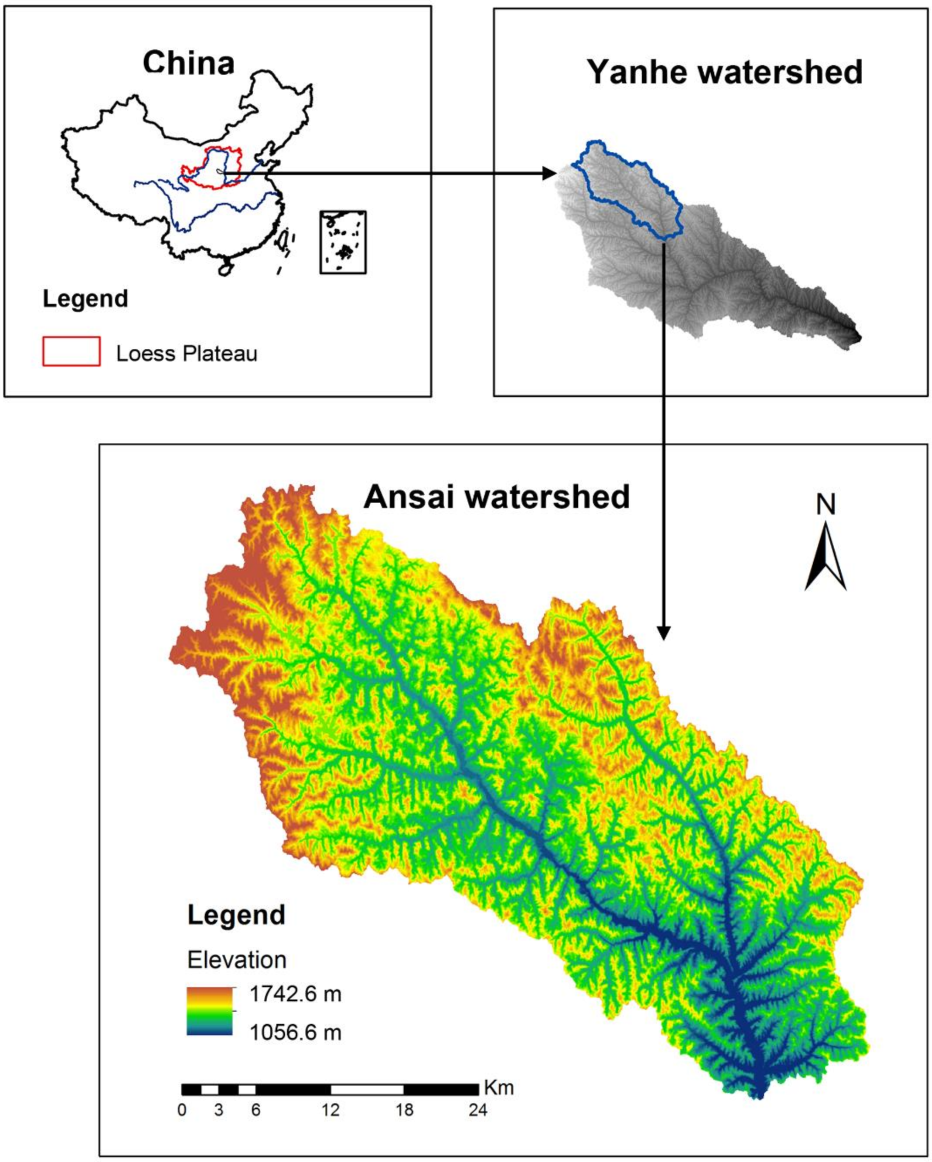


**Figure 1**. The location of the Ansai watershed.

## 2.2 Data sources

We downloaded Landsat TM images of 2000 and Landsat OLI images of 2014 from the USGS (http://glovis.usgs.gov/). Supervised classification was used to generate land-use maps with a 30m resolution. Land-use types included forest, shrub land, grassland, farmland, construction site, and water body. The classification accuracies are 86.4% and 89.4% in 2000 and 2014, respectively. We obtained meteorological data from China Meteorological Data Service Center (http://data.cma.cn/) and the Yellow River Hydrological Yearbook. We downloaded Digital Elevation Model (DEM) data (30m resolution) from Geospatial Data Cloud, Chinese Academy of Sciences (http: //www. gscloud.cn). We measured soil property (particle size composition and organic matter) in 151 sample plots in Ansai watershed in 2014 (Feng et al., 2017a), and the regression equations were constructed between soil properties and environmental factors (vegetation and topographic indices) (Feng, 2018). In this study, we obtained the soil property maps using these equations.

## 2.3 Assessment of ESs

We used the InVEST model to quantify soil erosion control (SEC), water yield (WY) and carbon sequestration (TC). The outputs of WY cannot be interpreted at the pixel level, as the model assumptions are based on processes investigated at the sub-watershed scale (Sharp et al., 2016). Thus, we used the Hydrology Tool of ArcGIS 10 to divide Ansai watershed into 817 sub-watersheds, and analyzed ESs at the sub-watershed level. The description of detailed calculation formulas for ESs can be appreciated in full in (ref). Here, we briefly summarize the key aspects of the three ES.

### 2.3.1 Soil erosion control (SEC)

"Sediment Delivery Ratio model" was used to calculate SEC in the latest version of the InVEST model, but observational data of sediment delivery ratio was scattered for the study area. Thus we complemented InVEST (version 2.5.6) with data and parameters from field observations and literature. The calculation process was as follows:

Soil loss from the pixel with existing vegetation was calculated using the Universal Soil Loss Equation (USLE):

$$USLE_x = R_x \cdot K_x \cdot LS_x \cdot C_x \cdot P_x \tag{1}$$

where $USLE_x$ is the average soil loss on pixel x; $R_x$ is the rainfall erosivity factor on pixel x; $K_x$ is the soil erodibility factor; $L_x$ is the slope length factor; $S_x$ is the slope steepness factor; $C_x$ is the cover and management factor; and $P_x$ is the support practice factor. *R* factor was calculated using the formula established by Zhang and Fu (2003), *K* factor was obtained using the method of William et al. (1984). We had constructed *C* factor estimation models by field survey for Ansai watershed (Feng et al., 2017b), so we obtained *C* value of various land-use types. *P* values in various land-use types were assigned according literature (Li et al., 2015).

If there is no vegetation present (bare soil) or support practice ($C = 1$, and $P = 1$), we could calculate the potential soil loss ($RKLS_x$):

$$RKLS_x = R_x \cdot K_x \cdot LS_x \tag{2}$$

Soil loss reduced by the pixel itself ($SORD_x$) was then calculated by subtracting $USLE_x$ from $RKLS_x$:

$$SORD_x = RKLS_x - USLE_x = R_x \cdot K_x \cdot LS_x \cdot (1 - C_x \cdot P_x) \tag{3}$$

Vegetation does not only keep sediment from being eroded where it grows, but also traps the sediment that had been eroded upstream. We estimated how much of the sediment eroded on all pixels would be trapped by downstream vegetation.

$$SEDR_x = SE_x \sum_{y=1}^{x-1} [USLE_y \prod_{z=y+1}^{x-1} (1 - SE_z)] \tag{4}$$

where $SEDR_x$ is the sediment interception amount on pixel *x*; $SE_x$ is the sediment interception rate of pixel $x$; $USLE_y$ is the soil loss from upstream pixel $y$; $SE_z$ is the sediment interception rate of upstream pixel $z$.

The total amount of soil erosion control ($SEC_x$) is equal to the sum of the soil loss reduced by the pixel itself ($SORD_x$) and the sediment intercepted through routing filtration ($SEDR_x$):

$$SEC_x = SORD_x + SEDR_x \tag{5}$$

The model generated the amounts of sediment retention and sediment loads both at watershed and sub-watershed level per each pixel. We calibrated the model by integrating observed sediment loading at the outlet of the watershed, the relative error between the estimated value and the observed value was only -1.9%. High values of SEC corresponds to lower rates of soil erosion…

### 2.3.2 Water yield (WY)

The water yield models do not differentiate among surface, subsurface and baseflow. Thus, annual water yield $Y_x$ for each pixel on the landscape $x$ was calculated as the difference between precipitation and evapotransipration:

$$Y_x = (1 - AET_x / P_x)P_x \tag{6}$$

where $AET_x$ is the annual actual evapotranspiration and $P_x$ the annual precipitation for each pixel $x$. Detail calculation process for $AET_x$ can be found in InVEST User's Book (Sharp et al., 2016). The annual precipitation map was obtained by Kriging interpolation method. Reference evapotranspiration was determined by "modified Hargreaves" equation (Droogers and Allen, 2002). Soil depth was obtained from Cold and Arid Regions Sciences Data Center (http://westdc.westgis.ac.cn). Vegetation rooting depth and evapotranspiration coefficient were obtained from local literature (Bao et al., 2016). Plant available water content was calculated by soil particle size and organic matter content (Zhou et al., 2005).

The model generated the water yields both at watershed and sub-watershed level. The model was calibrated with the observed data acquired from Ansai watershed, and the relative error between the estimated value and the observed value was only 2.4%.

### 2.3.3 Carbon sequestration (TC)

Carbon storage on a land parcel largely depends on the "pools" sizes of four carbon stocks: aboveground biomass, belowground biomass, litter and soil carbon. The InVEST Carbon Storage and Sequestration model was used to aggregate the amount of carbon stored in these pools according to the land-use maps. We used the carbon density of these pools on various land-use types in Ansai watershed as measured in a previous study (Feng et al., 2017a).

## 2.4 Influence factors

### 2.4.1 Deriving environmental factors

The "zonal statistics" tool of ArcGIS was used to derive average values of environmental factors in the sub-watersheds. Vegetation factors included land-use proportion and vegetation coverage (%); soil factors included sand, silt, and clay percentage composition, and soil organic matter content (g/kg); meteorological factors included rainfall and potential evapotranspiration (mm); slope gradient (°) was used as topography factors.

### 2.4.2 Calculating landscape pattern indices

The development of the software Fragstats has enabled researchers to calculate multiple landscape indices. We calculated nine landscape indices at different landscape and class levels (Table 1), and these indices contained most landscape information related to ESs.

**Table 1**. Landscape pattern indices selected in this study.

| Level | Type | Index | Description |
|---|---|---|---|
| Class | Area | PLAND | Quantifies the proportional abundance of each patch type in the landscape |
| | Density | PD | Number of patches on a per unit area |
| | | AREA | Reflects the degree of landscape fragmentation |
| | Shape | PARA | The ratio of perimeter (edge line) to area |
| | Contagion | AI | Measures the aggregation or extension of patches |
| | | DIVISION | Reflects the degree of separation or fragmentation of patches |
| | Connectivity | COHESION | Measures the physical connectedness of the corresponding patch type |
| Landscape | Diversity | PR | Measure the landscape composition |
| | | SHDI | Reflects the diversity of patch types |

PLAND: Percentage of Landscape, PD: Patch Density, AREA: Mean Patch Area, PARA: Perimeter-Area Ratio, AI: Aggregation Index, DIVISION: Landscape Division Index, COHESION: Patch Cohesion Index, PR: Patch Richness, SHDI: Shannon's Diversity Index

## 2.5. Trade-offs of ESs and statistical analyses

The root mean squared error (RMSE) is a simple and effective index for quantifying trade-offs of ESs (Bradford and D’Amato 2012), and was used by several previous studies (Lu et al., 2014; Feng et al., 2017a; Wang et al., 2017; Wu et al., 2018).

The multivariate analysis was used to explore the influence of drivers on ESs themselves and their trade-offs. The largest DCA (detrended correspondence analysis) gradient length was < 3.0, so the RDA (redundancy analysis) was selected and the significance of marginal and conditional effects were determined by Monte Carlo permutation test. After redundancy analysis, non-linear regression was used to explore the response relationship between ES trade-offs and single drivers. Pearson's correlation analysis was also performed between ES trade-offs and landscape pattern indices.

The RDA was conducted using CANOCO 5.0, and the correlation and regression analysis were conducted using SPSS 20.

# 3. Results

## 3.1 Temporal and spatial variation of ESs and their influencing factors

### 3.1.1 Temporal and spatial variation of ESs

As illustrated in Figure 2, grassland and farmland were the major land-use types and covered 96.8% of the area in 2000, whereas forest land, shrub land, and grassland were the major types in 2014, covering 88.5% of the area. The vegetation pattern in 2014 changed gradually from forest and shrub land (southeast or lower reaches) to grassland (northwest or upper reaches). The land-use transformation matrix showed that farmland was mainly converted to forestland and grassland, followed by shrub land, while grassland was mainly converted to forestland, followed by shrub land and farmland (Table 2). The primary driving factor was GFGP implemented in 1999, and secondly, local government had a preference for "afforestation" to "planting grass" in vegetation restoration activities.

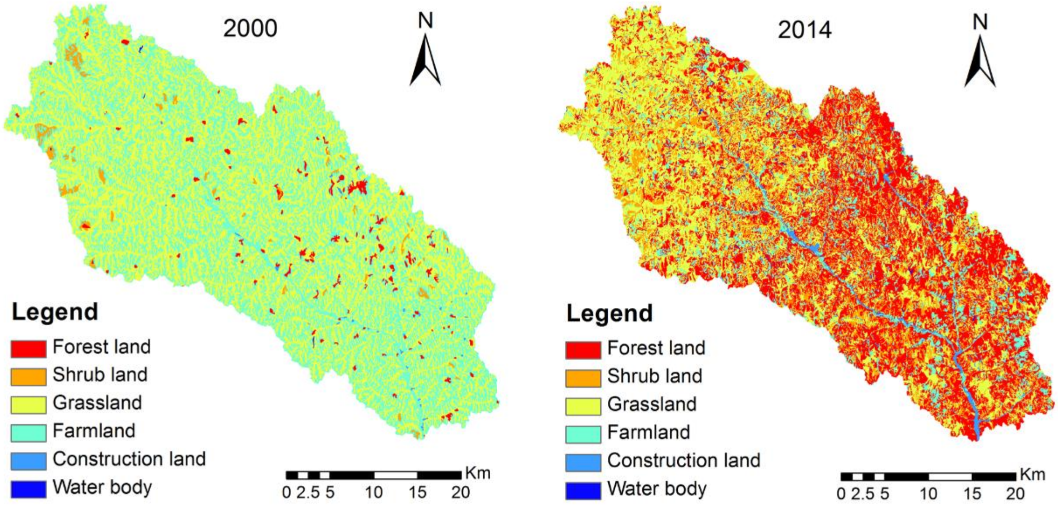


**Figure 2**. Land-use map of Ansai watershed in 2000 and 2014.

**Table 2**. Land-use transformation matrix from 2000 to 2014 ($km^2$).

| | 2014 | | | | | | |
|---|---|---|---|---|---|---|---|
| | ForL | ShrL | GraL | FarL | ConL | WatB | Total in 2000 |
| 2000 | | | | | | | |
| ForL | 12.78 | 1.65 | 3.65 | 1.33 | 0.66 | 0.07 | 20.14 |
| ShrL | 7.72 | 2.86 | 7.41 | 1.14 | 0.39 | 0.02 | 19.54 |
| GraL | 264.37 | 84.62 | 315.37 | 49.67 | 13.99 | 3.34 | 731.36 |
| FarL | 231.03 | 67.53 | 180.03 | 64.60 | 16.79 | 0.51 | 560.51 |
| ConL | 0.52 | 0.05 | 0.15 | 0.48 | 0.89 | 0.04 | 2.11 |
| WatB | 0.09 | 0.01 | 0.20 | 0.04 | 0.00 | 0.00 | 0.35 |
| Total in 2014 | 516.51 | 156.72 | 506.80 | 117.26 | 32.73 | 3.99 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Change from 2014 to 2000 | 496.37 | 137.18 | -224.56 | -443.25 | 30.62 | 3.64 |

Along with changes in land use, changes in ecosystem service were also observed (Figure 3). The average value of SEC and TC increased from 134.4 t/ha and 26.1 t/ha in 2000 to 158.3 t/ha and 47.4 t/ha in 2014, while WY decreased from 29.8 mm to 18.6 mm. Obviously, SEC and TC increased together, but at the cost of decreasing WY. Therefore, synergies were found between SEC and TC as well as the trade-offs between these two ESs and WY, confirming previous findings (Lü et al., 2012; Wu et al., 2018).

The spatial distribution of SEC is found to be similar between 2000 and 2014, showing a gradual decreasing trend from southeast to northwest. In 2000, WY gradually had lower values when moving from southeast to northwest, consistently with the spatial distribution of rainfall. On the other hand, WY did not exhibit obvious spatial layout in 2014. The valley floor along the main water channel is wide and flat, with high proportions of construction land and farmland and relatively lower consumption rates of water by vegetation transpiration. WY along the main water channel was thus larger than other places. Because TC is strictly coupled to vegetation type, spatial distribution of TC generally followed that of land-use.

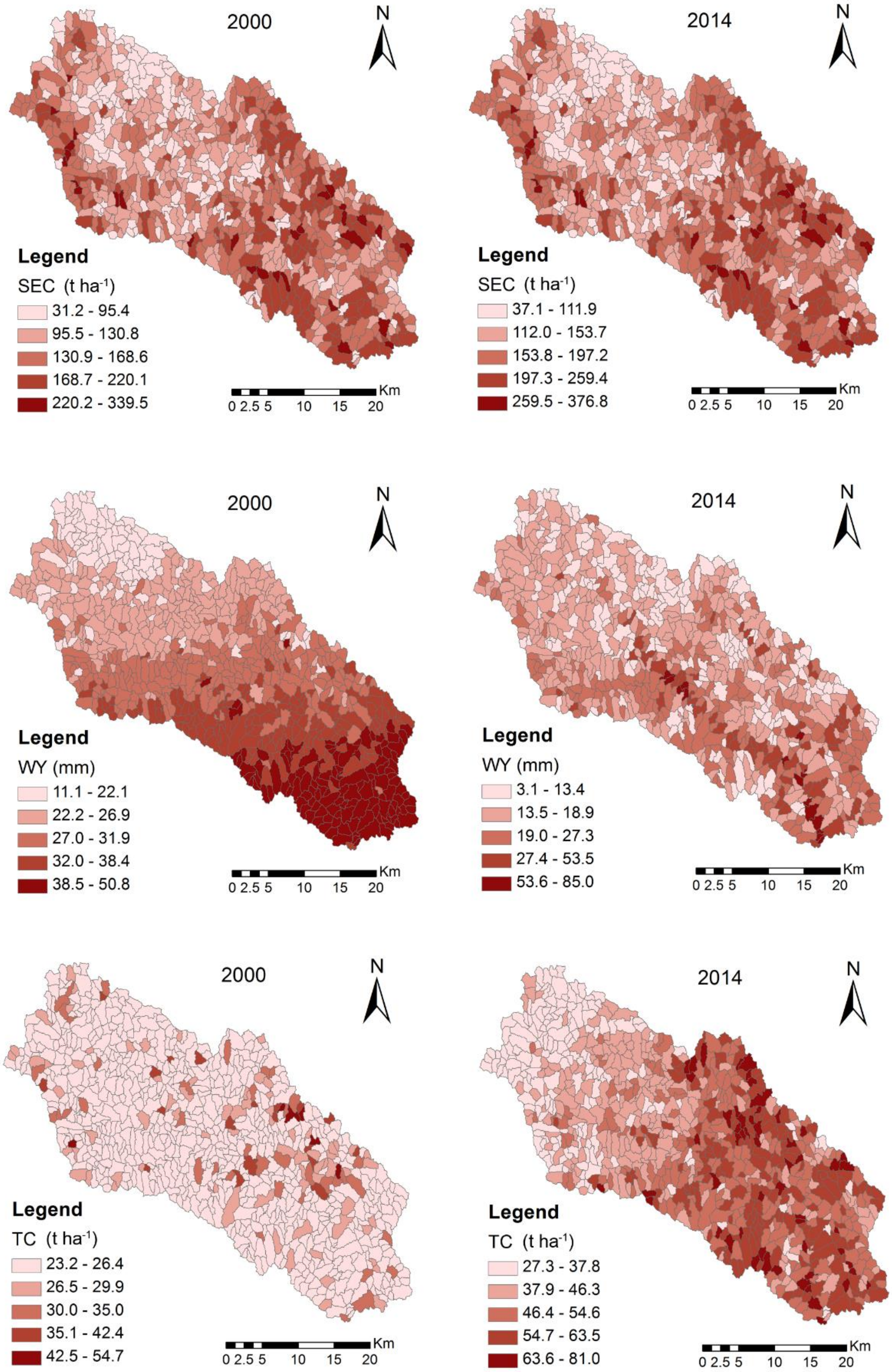


**Figure 3**. SEC, WY and TC in 2000 and 2014.

### 3.1.2 Effects of environmental factors on ESs

Table 3 shows the marginal and conditional effects of the variables by the Monte Carlo test. The marginal effects indicates the effects of the variables on the ESs, and the conditional effects indicates the effects after the anterior variables were eliminated.

Only the variables that significantly ($p<0.05$) affected ESs in 2000 are listed in Table 3. The marginal effect of slope gradient (SloG) on SEC was the highest (61.3%), and that of Vegetation type, vegetation cover rate (VegC), and rainfall amount (Raif) was secondary. The effect of FarL was negative, but that of ForL, ShrL, Raif, and VegC was positive. The influence of other variables was weak, and the marginal effects were below 1%. This means that

Vegetation type and VegC were the best explanatory variables to TC. The marginal effect of ForL reached 87.4%, secondly, that of VegC reached 20%, finally, that of FarL, ShrL, and GraL were all above 10%. Only the conditional effects of ForL, Shr, FarL, and GraL were significant, indicating the strong interaction effects that existed between environmental variables.

WY was mainly affected by Raif, with a marginal effect of 61.4%. Transpiration was non-existent in construction land and the water consumption by transpiration in farmland was low, thus these two land-use types had strong positive effect on WY. Similarly, the conditional effect of GraL was significant. Contrarily, the water consumption of ForL and ShrL was high. The effect of VegC on WY was by means of land-use types, so the conditional effect of VegC was not significant. SOM had negative effect on WY because it correlates with land-use typesand it is usually high in forest and shrub land (and in these cases it is the high transpiration that caused lower WY). The marginal effect of Alti was negative and significant, but the conditional effect was not significant. This is because the effect of Alti on WY is mainly implemented via land-use types: construction land and farmland are usually distributed at low altitudes, and forests are more abundant atelevated position.

The conditional effects eliminate the interactions among the variables, so the sum of conditional effects can represent the gross effects of variables on ESs. The drivers can explain 63.0%, 99.9%, and 99.3% of SEC, TC, and WY variation, respectively, indicating that the selected drivers were comprehensive and they included the environmental information.

**Table 3**. Marginal (MaE) and conditional effects (CoE) for ESs in 2000.

| SEC2000 | | | TC2000 | | | WY2000 | | |
|---|---|---|---|---|---|---|---|---|
| factors | MaE | CoE | factors | MaE | CoE | factors | MaE | CoE |
| SloG | 61.3 | 61.3 | ForL | 87.4 | 87.4 | Raif | 61.4 | 61.4 |
| FarL | 5.9 | | VegC | 20 | | ConL | 28.2 | 20.3 |
| Raif | 5.3 | 0.4 | FarL | 10.8 | <0.1 | FarL | 22.5 | 4.7 |
| VegC | 5.2 | | ShrL | 10.4 | 10.5 | Alti | 12.1 | |
| ShrL | 1.3 | 0.3 | GraL | 10.3 | 2 | Silt | 11.5 | |
| ForL | 1.2 | 0.5 | SloG | 1.5 | | Sand | 11.2 | 8 |
| Alti | 1 | | Raif | 1.3 | | SOM | 8.4 | <0.1 |
| SOM | 0.9 | 0.5 | Alti | 0.8 | | Clay | 8.3 | |
| GraL | 0.9 | | Silt | 0.6 | | ForL | 5.2 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ConL | 0.6 | | Sand | 0.5 | | ShrL | 5.1 | <0.1 |
| | | | $ET_0$ | 0.5 | | GraL | 4 | 4.9 |
| | | | | | | VegC | 2.5 | |
| | | | | | | $ET_0$ | 1.6 | <0.1 |
| Total | 83.6 | 63 | Total | 144.1 | 99.9 | Total | 182 | 99.3 |

Environmental factors in grey shadow had negative effects on ESs, and the other factors had positive effects; land-use type represented the proportion of this land-use type.

In 2014, the influence of SloG on SEC was much higher than the other factors, and the marginal effect reached 59.4% (Table 4). The Raif and forest had positive effects on SEC, but grassland had negative effect, and their marginal effects were higher than those of 2000. The Silt and SOM promote the formation of soil aggregates and enhance soil anti-erodibility, but these effects on SEC were below 1%. The forest, grassland, and VegC had determinative effects (MaE>50%) on TC. The marginal effect of construction land for WY was the highest, that of Raif, $ET_0$, and Alti was the second, and that of farmland and soil partial size was the third. The main differences with the year 2000 are…

The drivers can explain 63.8%, 91.9%, and 97.9% of SEC, TC, and WY variation, respectively. The sum of the marginal effect on TC reached 408.8%, denoting that strong interaction effects existed between drivers.

**Table 4**. Marginal (MaE) and conditional effects (CoE) for ESs in 2014.

| SEC2014 | TC2014 | WY2014 |
|---|---|---|

| factors | MaE | CoE | factors | MaE | CoE | factors | MaE | CoE |
|---|---|---|---|---|---|---|---|---|
| SloG | 59.4 | 59.4 | ForL | 86 | 86 | ConL | 44.5 | 44.5 |
| $ET_0$ | 13.3 | 4.1 | VegC | 65 | 1 | $ET_0$ | 14.4 | <0.1 |
| Raif | 13.2 | | GraL | 63.5 | 0.4 | Alti | 14.3 | |
| FarL | 6.2 | | SOM | 45.4 | | Raif | 14.1 | 24.5 |
| VegC | 5.1 | | Raif | 33 | 0.1 | FarL | 12.7 | 1.8 |
| ForL | 4.2 | | $ET_0$ | 32 | | Silt | 12.4 | |
| GraL | 1.8 | | Clay | 19.4 | | Sand | 12.3 | 0.3 |
| ShrL | 1.3 | | Sand | 18.7 | | Clay | 10.3 | |
| WatB | 1.1 | | Silt | 18.5 | | ShrL | 5.8 | 15.7 |
| Silt | 0.5 | | Alti | 15.1 | | ForL | 3.6 | 11.1 |
| | | | ShrL | 4.6 | 4.3 | SloG | 2.5 | |
| SOM | | 0.3 | SloG | 3.5 | 0.1 | WatB | 1.7 | |
| | | | ConL | 2.6 | | SOM | 1.5 | |
| | | | WatB | 1.5 | | VegC | 0.9 | |
| | | | | | | GraL | | <0.1 |
| Total | 106.1 | 63.8 | Total | 408.8 | 91.9 | Total | 151 | 97.9 |

Environmental factors in grey shadow had negative effects on ESs, and the other factors had positive effects; land-use type such as ShrL represented the proportion of this land-use type.

## 3.2 Quantifying trade-offs between ESs

We observed changes in the spatial distribution of trade-offs between ESs (Figure 4). In 2000, the high value areas of SEC-WY trade-offs were distributed in northeast and northwest areas of the Ansai watershed, whereas the low values were relatively continuous and distributed in the north central region. TC-WY trade-offs decreased gradually from south to north. Areas with high values presented banding distribution along the south edge of watershed, but the low value areas were very continuous and distributed in the north region. The spatial pattern of trade-offs was highly correlated to the pattern of individual ES. The high value areas of SEC-WY trade-offs coincided with high value areas of SEC and low value areas of WY, whereas the high value areas of TC-WY trade-offs coincided with low value areas of TC and high value areas of WY. The degree of relative waxing and waning between ESs determined trade-offs intensity.

In 2014, the spatial distribution of SEC-WY and TC-WY trade-off was similar. Trade-off values gradually decreased from southeast to northwest, and they became relatively high in the edge of northwest area. The distribution of trade-offs was consistent with land-use types. For example, forest and shrub were the dominant vegetation in southeast, causing higher SEC and TC, but lower WY.

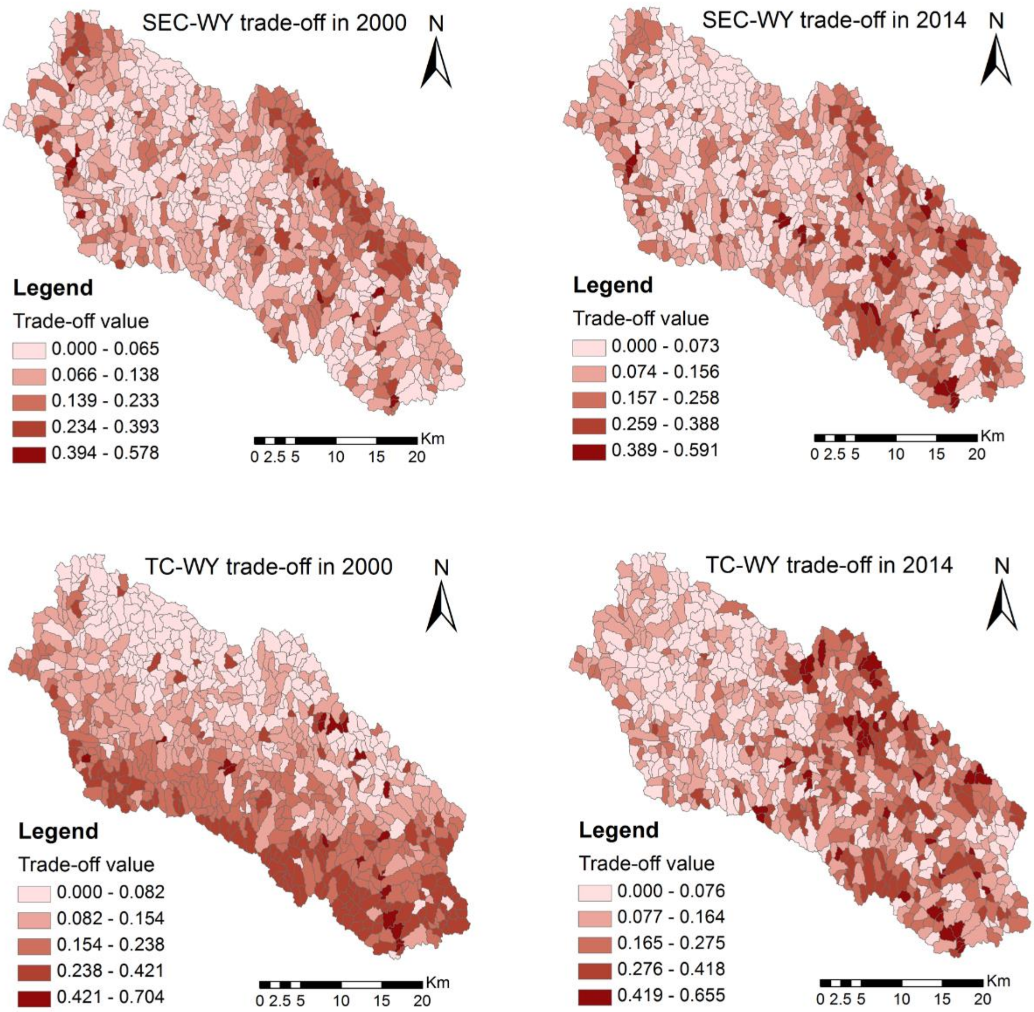


**Figure 4**. The spatial distribution of trade-offs between ESs.

## 3.3 Redundancy analysis (RDA) of trade-offs and drivers of ESs

The environmental variables that significantly ($p<0.05$) affected the trade-offs of ESs are listed in Table 5. The explanatory capability of construction land on SEC-WY trade-offs was the highest in 2000, but the marginal effect was 12.1% only, and SloG, forest, shrub land, and VegC were the secondary drivers. These variables were positively correlated with the trade-off. By combining the effects of variables on individual ESs, we found that: (i) WY increased but SEC decreased as the proportion of construction land increased, whereas (ii) WY decreased but SEC increased as the forest, shrub, and VegC increased. Therefore, these variables exacerbated ESs trade-offs as opposed to grassland which could restrain trade-offs to some extent. For TC-WY trade-offs in 2000, the marginal effects of Raif, construction land and grassland were the highest (>19%). Raif, construction land, farmland, and Silt were positively correlated with WY and negatively correlated with TC, whereas forest and SOM were positively correlated with TC and negatively correlated with WY. Thus, these drivers exacerbated ESs conflicts. Grassland restrained TC-WY trade-offs as above.

The influence mechanism of drivers on SEC-WY trade-offs in 2014 was similar to that in 2000. Drivers influenced the degree of relative waxing and waning between ESs, or caused unidirectional changes of ESs at an uneven pace or rate. Grassland also restrained trade-offs as that in 2000. However, the marginal effect of construction land decreased from the first place to the seventh place from 2000 to 2014, but the effect of grassland rose to the second place.

For TC-WY trade-offs in 2014, forest, grassland, and VegC were the top three drivers, and the marginal effects of Raif and construction land fell to the 5th and 13th place. This means that vegetation became the primary factor controlling ESs trade-offs after of 15 years of ecological restoration.

The explanatory capability of the drivers for the SEC-WY trade-off was substantially below those for SEC and WY, and the sum of conditional effect was only 36.4% and 33.8% in 2000 and 2014, respectively. This explanatory capability for the TC-WY trade-off was 73.7% and 48.7% in 2000 and 2014, respectively. The drivers influenced the ESs first and then the trade-off, but the influence mechanism was more complex, and the influence power often decreased (Feng et al., 2017a).

**Table 5**. Marginal (MaE) and conditional effects (CoE) for ESs trade-offs.

| Year | SEC-WY trade-off | | | TC-WY trade-off | | |
|---|---|---|---|---|---|---|
| | factors | MaE | CoE | factors | MaE | CoE |
| 2000 | ConL | 12.1 | 12.1 | Raif | 36.1 | 36.1 |
| | SloG | 8.9 | 11.7 | ConL | 20.6 | 15.4 |
| | ForL | 7.4 | 6 | GraL | 19.4 | |
| | ShrL | 4.9 | 4.3 | FarL | 14.1 | 4.9 |
| | VegC | 3.5 | | ForL | 8.3 | 10 |
| | FarL | 2.8 | | Alti | 7.6 | |
| | GraL | 1.6 | | Silt | 7.4 | |
| | $ET_0$ | 0.7 | | SOM | 7.4 | |
| | Raif | | 1.8 | Sand | 7.3 | |
| | | | | Clay | 5.9 | |
| | | | | Sand | | 6.8 |
| | | | | $ET_0$ | | 0.5 |
| | Total | 41.9 | 35.9 | Total | 134.1 | 73.7 |
| 2014 | SloG | 19.9 | 19.9 | ForL | 42.7 | 42.7 |
| | GraL | 10.1 | 10.8 | GraL | 26.9 | 1.6 |

| | | | | | |
|---|---|---|---|---|---|
| ForL | 7.7 | | VegC | 24.5 | |
| Raif | 6.2 | | SOM | 11.7 | |
| $ET_0$ | 6.1 | | Raif | 9.9 | |
| VegC | 5.7 | | $ET_0$ | 9.7 | |
| ConL | 3.3 | 2.1 | SloG | 4.5 | 0.5 |
| ShrL | 1.9 | 0.4 | ShrL | 2.5 | |
| FarL | 1.5 | | Clay | 2.3 | |
| SOM | 1.2 | | FarL | 1.9 | 2.5 |
| Silt | 1 | | Sand | 1.8 | |
| Sand | 0.9 | | Silt | 1.8 | |
| WatB | 0.8 | | ConL | 1.3 | |
| Clay | | 0.6 | WatB | 1.2 | |
| | | | Alti | 1 | 1.4 |
| Total | 66.3 | 33.8 | Total | 143.7 | 48.7 |

Environmental factors in grey shadow had negative effects on ESs, and the other factors had positive effects; land-use type such as ShrL represented the proportion of this land-use type.

## 3.4 Relationship between ESs trade-offs and single drivers

In order to further analyze the effects of drivers on ESs trade-offs, the regression analysis between trade-offs intensity and single driver was conducted (Table 6). The coefficient of determination, $R^2$, reflects the proportion of total variance in trade-offs values attributed to the driver. The proportion of construction, forest, and shrub land can influence SEC-WY trade-off to some extent, and the $R^2$ of construction land was the highest (69.4%). The regression coefficients reflect the effect of independent variable on dependent variable. The regression coefficients of the three land-use types were positive and they aggravate trade-off, the effect of construction land was about one order of magnitude higher than that of forest and shrub land, and the effect of forest was one time higher than that of shrub land.

Raif was an important positive variable for TC-WY trade-off. Raif caused runoff but its effect on carbon storage was little because of the planted vegetation , thus Raif can increase the trade-off. The effect of construction land was about one order of magnitude higher than that of forest, grassland, and farmland, and the effect of forest was more than one time higher than that of grassland and farmland, but grassland constrained the trade-off intensity.

**Table 6**. Regression analysis between environmental factors and ESs trade-offs.

| Year | Regression equation | $R^2$ | *P* value | Threshold value |
|---|---|---|---|---|
| 2000 | SEC/WY=$6.10\times10^{-2}$ConL +$4.55\times10^{-2}$ | 0.69 | <0.001 | |
| | SEC/WY=$2.88\times10^{-3}$SloG $^{2}$-$8.93\times10^{-2}$SloG +$7.65\times10^{-1}$ | 0.15 | <0.001 | 15.5 º |
| | SEC/WY=$5.30\times10^{-3}$ForL +$8.98\times10^{-2}$ | 0.24 | <0.001 | |
| | SEC/WY=$2.59\times10^{-3}$ShrL +$1.15\times10^{-1}$ | 0.12 | <0.001 | |
| | TC/WY=$5.78\times10^{-3}$Raif -1.690 | 0.36 | <0.001 | |

| | | | | |
|---|---|---|---|---|
| | $TC/WY=5.57\times10^{-2}ConL+1.93\times10^{-1}$ | 0.59 | <0.001 | |
| | $TC/WY=-4.03\times10^{-3}GraL+3.72\times10^{-1}$ | 0.19 | <0.001 | |
| | $TC/WY=4.06\times10^{-3}FarL-1.98\times10^{-2}$ | 0.14 | <0.001 | |
| | $TC/WY=9.15\times10^{-3}ForL+8.31\times10^{-2}$ | 0.38 | <0.001 | |
| 2014 | $SEC/WY=4.55\times10^{-3}SloG^2-1.39\times10^{-1}SloG+1.128$ | 0.31 | <0.001 | 15.16 º |
| | $SEC/WY=-1.68\times10^{-3}GraL+1.89\times10^{-1}$ | 0.10 | <0.001 | |
| | $TC/WY=1.26\times10^{-4}ForL^2-5.54\times10^{-3}ForL+1.32\times10^{-1}$ | 0.62 | <0.001 | 21.98% |
| | $TC/WY=8.91\times10^{-5}GraL^2-1.06\times10^{-2}GraL+3.91\times10^{-1}$ | 0.36 | <0.001 | 59.48% |
| | $TC/WY=5.53\times10^{-4}VegC^2-5.79\times10^{-2}VegC+1.583$ | 0.38 | <0.001 | 52.35% |
| | $TC/WY=3.63\times10^{-2}SOM-2.08\times10^{-1}$ | 0.12 | <0.001 | |

SEC/WY：Trade-off value between SEC and WY, TC/WY: Trade-off value between TC and WY, $R^2$: coefficients of determination.

Grassland can restrain SEC-WY trade-off in 2014. The fitting curve between SloG and SEC-WY trade-off was an upward parabola, indicating the existence of a threshold value (15.16º) to minimize the trade-off intensity. If SloG<15.16º, trade-off intensity decreased as SloG increased; if SloG>15.16º, trade-off intensity increased as SloG increased. This phenomenon was related to the distribution of local vegetation with slope. When SloG>15.16º, the proportion of forest increased and that of farmland and construction land decreased as SloG increased. At the same time, SEC was enhanced and WY decreased, and thus trade-off was exacerbated. On the other hand, when SloG<15.16º farmland and construction land were dominant in areaswhere WY was high and SEC was low, so trade-off was also exacerbated. Grassland, forest and shrub land were arranged together with certain proportion on gentle slope area where WY slightly decreased and SEC increased, so trade-off was dampened. The trade-off intensity would be reduced to a minimum when SloG=15.16º.

The fitting curves between TC-WY trade-off and forest, grassland, and VegC were all upward parabolas in 2014.. Therefore there were threshold values of land-use proportion and VegC that minimized the trade-off intensity. For small watershed, if fores smaller than t22% WY was high and TC was low (trade-off intensity was high), and increasing forest cover would promote the balance between WY and TC. If the proportion of forest is biggher than 22%, ESs relationship reversed, WY was low and TC was high. Therefore, the proportion of forest is to be controlled at about 22%. Similarly, the threshold value of grassland proportion was 59%. Consequently, if only considering the relationship between WY and TC, the proportion of forest is too high and that of grassland is too low at present in the Ansai watershed. In future ecological restoration, we should establishment of grassland instead of forest can alleviate the TC-WY.

## 3.5 The effects of landscape pattern on ESs trade-offs

In order to regulate current ESs, we also analyzed the relationship between landscape pattern and ESs trade-offs in 2014. As illustrated in Table 7, the response direction of SEC-WY and TC-WY trade-offs to landscape pattern metrics was consistent, so it is simply as referred to “trade-offs” hereafter. For landscape pattern metrics of forest patch at class level, PLAND, AREA, COHESION, and AI were significantly positively correlated with trade-offs, whereas PD, PARA, and DIVISION were significantly negatively correlated with trade-offs. The effects of landscape pattern metrics of grassland on trade-offs were contrary to that of forests. The response direction of trade-offs to landscape pattern metrics of construction land was consistent with that of forest. The correlation between trade-offs and pattern metrics of other land-use patches was relatively weak. Only PLAND, PD, and DIVISION of shrub land were significantly positively correlated with the trade-offs, whereas PLAND and PD of water body were significantly negatively correlated. The effects of pattern metrics at landscape level were weaker than that at class level.

Therefore, not only the proportion of land-use types, but also land-use distribution pattern influenced ESs trade-offs. Possible management options to mitigate these trade-offs include a decline in forest proportion and individual forest patch area, constrain spatial aggregation of forest patches and reduce their proximity, increase the diversity of patches and their spatial complexity, increase the proportion of forest patch edges. We should also increase grassland proportion and patch areas, by enhancing spatial aggregation and proximity of grassland patches and reduce fragmentation of grassland.These practices will lead to a reduction of water consumption and an increase of intercepting sediments. At the same time, increases in carbon storage are achieved, thereby being instrumental to balance multiple ESs and climate change mitigation.

Changes of landscape composition directly influence the spatial distribution of ESs, while changes of landscape configuration indirectly influence ESs by altering ecological processes (Fagerholm et al., 2012; Jia et al., 2014). For example, a highly heterogeneous landscape can have a higher capacity for pest and disease control, while a less heterogeneous landscape can have a higher potential for climate control (Frueh-Mueller et al., 2018). Moreover, landscape pattern also can affect ESs relationship: a win-win situation for grassland ESs can be achieved by increasing grassland aggregation (Hao et al., 2017). Therefore, landscape pattern analysis can aid policymakers in landscape management.

**Table 7**. Pearson's correlation analysis between trade-off intensity and landscape pattern metrics.

| Metrics | TC-WY trade-off | | | | | | SEC-WY trade-off | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ForL | ShrL | GraL | FarL | ConL | WatB | ForL | ShrL | GraL | FarL | ConL | WatB |
| PLAND | 0.78** | -0.34** | -0.72** | 0.08 | 0.47** | -0.24 | 0.58** | -0.17 | -0.56** | 0.00 | 0.47** | -0.30* |
| PD | -0.36** | -0.30** | 0.12 | 0.01 | 0.20 | -0.38** | -0.47** | -0.24* | -0.13 | -0.08 | 0.01 | -0.38** |
| AREA | 0.67** | -0.18 | -0.44** | 0.17 | 0.40** | 0.14 | 0.72** | -0.06 | -0.29** | 0.18 | 0.46** | 0.18 |
| PARA | -0.73** | 0.19 | 0.62** | -0.15 | -0.32** | -0.07 | -0.67** | 0.07 | 0.35** | -0.19 | -0.36** | -0.12 |
| COHESION | 0.72** | -0.16 | -0.77** | 0.22 | 0.29** | 0.08 | 0.55** | -0.08 | -0.54** | 0.21 | 0.32** | 0.10 |
| AI | 0.72** | -0.14 | -0.61** | 0.06 | 0.26* | 0.14 | 0.68** | 0.00 | -0.32** | 0.11 | 0.32** | 0.26 |
| DIVISION | -0.73** | 0.26* | 0.48** | -0.08 | -0.44** | 0.08 | -0.71** | 0.22* | 0.33** | -0.00 | -0.45** | 0.17 |
| PR | -0.23* | | | | | | -0.35* | | | | | |
| SHDI | -0.16 | | | | | | -0.20 | | | | | |

* and ** represent significance at the levels of 0.05 and 0.01 respectively, PLAND: Percentage of Landscape, PD: Patch Density, AREA: Mean Patch Area, PARA: Perimeter-Area Ratio, AI: Aggregation Index, DIVISION: Landscape Division Index, COHESION: Patch Cohesion Index, PR: Patch Richness, SHDI: Shannon's Diversity Index

# 4. Discussion

## 4.1 The influence mechanisms of ESs trade-offs

The following main considerations emerge from the ESs investigated in this study. SEC is mainly affected by rainfall, topography, soil property, vegetation, and support practice. WY is affected by rainfall, potential evapotranspiration, soil property, and vegetation cover. TC is mainly affected by vegetation. Among drivers for ESs, meteorological and topographical largely depend on physical aspects of the terrain and local climate, which are relatively constant over time. By contrast, vegetation cover through land use is a factor that policy makers and local communities can directly influence to help regulation of ESs. Forests are benificial to soil erosion control and carbon sequestration (Fu et al., 2011; Lü et al., 2012; Feng et al., 2017a), but forests also result in higher water consumption, thus reducing the availability of local runoff water (Wang and Fu, 2013), even causing soil desiccation (Wang et al., 2013). This is particularly true for ecosystems in arid and semi-arid environments. Contrarily, grassland is usually a preferred vegetation type in arid areas (Chisholm et al., 2010; Wu et al., 2018). Because of its comparably lower water consumption, grassland can support higher water supply while maintaining other ESs at a relatively high level (Mark and Dickinson, 2008; Feng et al., 2017a; Wu et al., 2018). Generally, soil erosion control and carbon sequestration on farmland is lower than forests (Feng et al., 2017a), but the water yield is higher (Wu et al., 2018).

In this study, we investigated the interaction between SEC and WY as well as that between TC and WY, and the dominant drivers can be appreciated in Figure 5. SEC and WY had no interactions with one another, but the two ESs had shared drivers. Forest and shrubland benefited SEC but at the same time they restricted WY, meaning that alteration of these shared drivers may lead to a "win-lose" situation by enhancing one ES at the costs of another. In other words, forest and shrubland proportions can not be too high neither too low, an a appropriate proportion is ideal to realize the balance between SEC and WY. In addition, slope gradient, grassland and construction land were independent drivers (non-shared drivers) for SEC and TC respectively, providing an opportunity to mitigate tradeoffs by permitting manipulation of one ES without other adverse side effects. For example, increasing grassland proportion will only enhance WY, so decreasing the corresponding trade-off.

There was a unidirectional interaction between TC and WY. Because the vegetation was artificially planted in the study area, the carbon sequestration clearly affected water yield, but not vice versa. As the shared driver, rainfall promoted WY, and it slightly promoted TC as well. Grassland and farmland benifited WY but restricted TC, while forestland had contrary effects. Nevertheless, forestland aggravated the trade-off and grassland can restrain it. This is confirmed by other studies in waterlimited areas (Wu et al., 2018). Construction land was an independent driver for WY, but regulating construction land was unfeasible at the watershed scale.

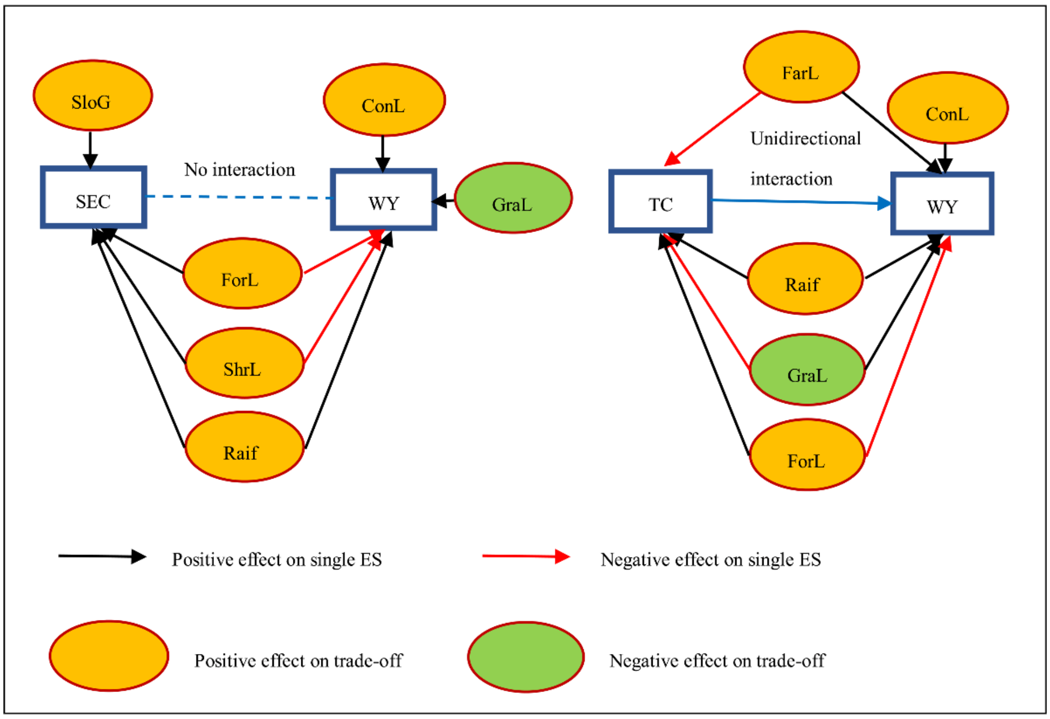


**Figure 5**. Effects of drivers on ecosystem services and their trade-offs (distilling from conditionnal

Shared and independent drivers provide leverage points for altering ES. Management of multiple

ESs considering mechanisms of trade-offs is a relatively new field, and the number of case studies is increasing.

## 4.2 Subarea and recommendations for ESs regulation based on trade-offs

### 4.2.1 Subarea based on ESs trade-offs intensity

The spatial distribution of trade-offs intensity provided a basis for zonal management of ESs. Some researchers defined the highest 20% and lowest 20% of ESs and their trade-offs as hot spot and cold spot, respectively (Zheng et al., 2016). According to this method, we find the areas with the highest 20% and lowest 20% of trade-offs intensity, so to identify strong and weak trade-off subareas. As illustrated in Figure 6 and 7, strong and weak trade-off subareas of SEC-WY were similar to that of TC-WY. Weak trade-off subareas were mainly distributed in the northwest, and strong trade-off subareas were distributed in the middle and southeast.

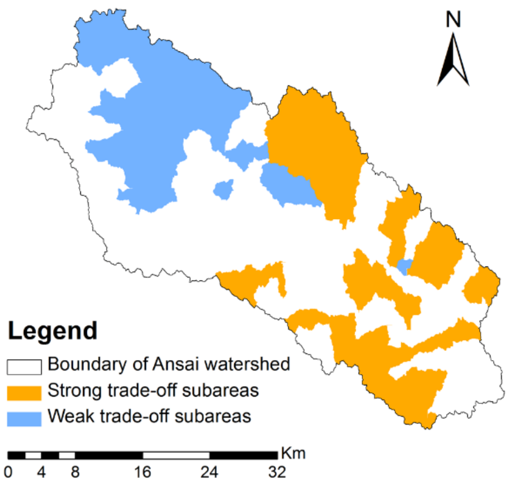


**Figure 6**. Subarea based on ESs trade-offs intensity.

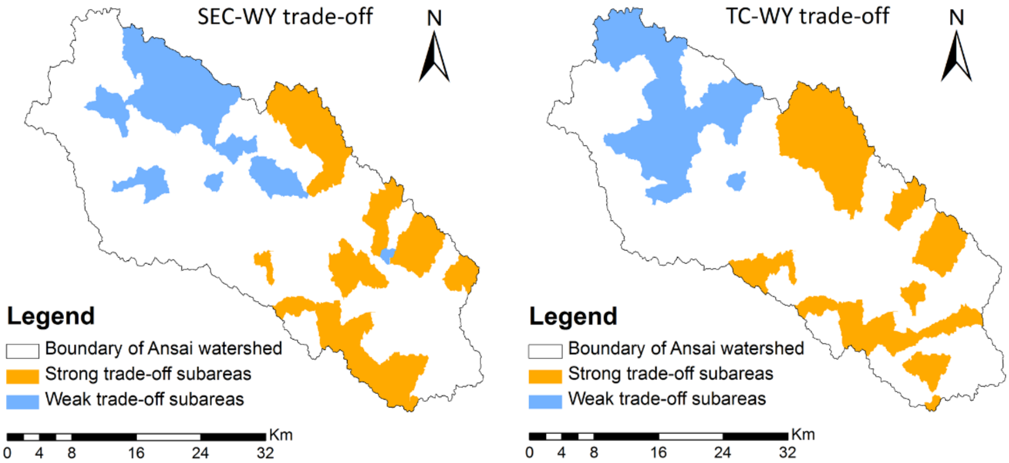


**Figure 7**. Superposed graph for SEC-WY and TC-WY trade-off subarea.

Landscape pattern at a class level is easier to manipulate than that at a landscape level in ESs regulation. Table 8 showed pattern metric values in weak trade-off subarea, strong trade-off subarea, and the whole watershed, respectively, providing a reference for regulating trade-off intensity by means of pattern metric. The pattern metric can be manipulated to achieve the average or the weak trade-off intensity level. For example, PLAND of forest patch in strong trade-off subarea was 54.3-55.1%, and that in weak trade-off subarea was 21.5-27.9% that could be set as regulating target for strong trade-off subarea. Likewise, the regulating target of PLAND of grassland patch was 46.1-53.7% for strong trade-off subarea. Moreover, the regulating target of AREA of forest patch was 2.0-2.4ha. Similarly, we can determine regulating targets for PARA, AI, DIVISION, and COHESION. The regulation direction was as follows: increasing complexity and decreasing aggregation of forest patch, and the regulation direction for grassland patch was opposite. However, it is difficult to manipulate the complex pattern metrics in vegetation restoration practice.

**Table 8**. Landscape pattern metrics in strong trade-off subarea, weak trade-off subarea, and the whole watershed.

| Land-use type | trade-off subarea | PLAND | PD | AREA | PARA | COHESION | DIVISION | AI |
|---|---|---|---|---|---|---|---|---|
| ForL | Weak subarea of TC/WY | 21.5 | 13.4 | 2.0 | 379.9 | 87.7 | 1.0 | 73.3 |
| | Weak subarea of SEC/WY | 27.9 | 15.2 | 2.4 | 364.5 | 89.4 | 1.0 | 74.4 |
| | Strong subarea of TC/WY | 55.1 | 7.2 | 8.9 | 200.2 | 97.7 | 0.9 | 86.1 |
| | Strong subarea of SEC/WY | 54.3 | 5.7 | 10.9 | 182.6 | 97.9 | 0.9 | 87.5 |
| | Mean value in watershed | 38.1 | 10.1 | 5.1 | 284.4 | 93.4 | 1.0 | 80.0 |
| ShrL | Weak subarea of TC/WY | 16.3 | 9.8 | 2.3 | 364.6 | 87.4 | 1.0 | 74.7 |
| | Weak subarea of SEC/WY | 15.3 | 10.3 | 2.1 | 399.7 | 85.0 | 1.0 | 72.2 |
| | Strong subarea of TC/WY | 10.2 | 6.4 | 1.5 | 429.1 | 84.6 | 1.0 | 70.3 |
| | Strong subarea of SEC/WY | 11.3 | 6.0 | 2.0 | 407.9 | 84.5 | 1.0 | 72.4 |
| | Mean value in watershed | 12.5 | 7.3 | 2.0 | 402.4 | 85.4 | 1.0 | 72.0 |
| GraL | Weak subarea of TC/WY | 53.7 | 9.4 | 10.1 | 239.5 | 97.6 | 0.8 | 83.3 |
| | Weak subarea of SEC/WY | 46.1 | 11.4 | 7.3 | 286.0 | 96.2 | 0.9 | 80.0 |
| | Strong subarea of TC/WY | 20.8 | 10.8 | 2.2 | 380.5 | 89.7 | 1.0 | 73.2 |
| | Strong subarea of SEC/WY | 22.5 | 8.7 | 3.0 | 340.2 | 91.4 | 1.0 | 76.3 |
| | Mean value in watershed | 37.5 | 9.8 | 5.9 | 293.1 | 94.8 | 0.9 | 79.3 |
| FarL | Weak subarea of TC/WY | 6.3 | 3.1 | 2.0 | 395.6 | 83.8 | 1.0 | 74.4 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Weak subarea of SEC/WY | 8.2 | 3.5 | 2.2 | 375.2 | 84.9 | 1.0 | 76.6 |
| | Strong subarea of TC/WY | 9.1 | 3.2 | 3.3 | 336.4 | 88.5 | 1.0 | 77.1 |
| | Strong subarea of SEC/WY | 8.2 | 3.0 | 3.6 | 329.2 | 88.9 | 1.0 | 77.8 |
| | Mean value in watershed | 9.0 | 3.1 | 3.1 | 336.4 | 88.1 | 1.0 | 77.6 |
| ConL | Weak subarea of TC/WY | 1.9 | 3.3 | 0.6 | 688.6 | 60.3 | 1.0 | 53.2 |
| | Weak subarea of SEC/WY | 2.1 | 3.5 | 0.7 | 625.5 | 66.2 | 1.0 | 60.2 |
| | Strong subarea of TC/WY | 5.2 | 4.5 | 2.4 | 502.0 | 75.6 | 1.0 | 65.5 |
| | Strong subarea of SEC/WY | 4.6 | 3.3 | 2.6 | 485.6 | 76.9 | 1.0 | 67.7 |
| | Mean value in watershed | 2.9 | 3.7 | 1.1 | 581.2 | 69.8 | 1.0 | 61.2 |
| WarB | Weak subarea of TC/WY | 0.5 | 1.7 | 0.3 | 889.5 | 46.3 | 1.0 | 45.9 |
| | Weak subarea of SEC/WY | 0.7 | 1.7 | 0.4 | 834.9 | 51.4 | 1.0 | 48.8 |
| | Strong subarea of TC/WY | 0.1 | 0.3 | 0.5 | 826.1 | 55.6 | 1.0 | 56.8 |
| | Strong subarea of SEC/WY | 0.2 | 0.4 | 1.0 | 755.0 | 59.8 | 1.0 | 62.0 |
| | Mean value in watershed | 0.4 | 0.9 | 0.7 | 786.0 | 56.6 | 1.0 | 57.6 |

SEC/WY: Trade-off between SEC and WY, TC/WY: Trade-off between TC and WY, PLAND: Percentage of Landscape, PD: Patch Density, AREA: Mean Patch Area, PARA: Perimeter-Area Ratio, AI: Aggregation Index, DIVISION: Landscape Division Index, COHESION: Patch Cohesion Index, PR: Patch Richness, SHDI: Shannon's Diversity Index

#### 4.2.2 Recommendations for ESs regulation

Based on land-use proportion and landscape pattern metrics in different subareas and the response functions between trade-offs intensity and environmental factors, forest should be generally restricted, and water-saving grassland and shrub land expanded, particularly in area with strong trade-offs. It is recommended that forest proportion needs to be controlled at 20-30%, whereas grassland proportion needs to be controlled at 45-60%. These shares will ensure that the weak trade-off intensity is achieved. The threshold of slope gradient was 15º, the place with this slope gradient was a transitional area from farmland to forestland, where the ESs conflict was abated, indicating that proportion allocation and spatial mosaic of different land-use types are important. Besides farmland, certain amounts of cultivated grass and economic forest can be arranged on gentle slope, which is beneficial to WY on the premise of maintaining SEC. Besides forest, certain amount of water-saving grassland and shrub land can be arranged on steep slope, and the balance among SEC, TC, and WY can be realized. Finally, we proposed the mode of ecological restoration in the Ansai watershed, taking the contiguous grassland as the matrix, in which the small forestland patch with more edges can be set, and shrub land can be increased properly (large adjustment of farmland was not necessary).

With regard to topography, slope gradient was an important factor affecting ESs. The actual soil loss increased as the slope gradient increased (Feng et al., 2016), and the SEC also enhanced which was because the increment of potential soil loss was greater than actual soil loss with slope gradient. The reduction of actual soil loss is the primary objective in soil conservation activity, and it is the basis of agricultural production. Therefore, building bench terraces and conducting micro-landform modification (fish scale pit, level trench etc.) are recommended to reduce soil loss and better utilize water resourceb .

With regard to soil, the soil nutrient condition is better in forest and shrub land, but it is often lower in grassland. The reason is that grassland is mostly distributed in arid and barren areas. Thus, planting legume grass and applying organic fertilizer on natural barren slope are recommended. After the soil conditions are improved, we can arrange water-saving shrub and forest to enhance SEC and TC.

With regard to other measures, we can construct cistern to fully utilize rainwater resources, cover the soil surface to reduce water evaporation and control soil loss, use water-retaining agents to decrease water consumption, and employ conservation tillage and agro-forestry planting system.

# 5. Conclusion

In 2014, GFGP implemented for more than 10 years in the Ansai watershed changed the land-use types significantly compared to those in 2000. Accordingly, SEC and TC increased by 17.8% and 82.1%, while WY declined by 37.6%. Synergies are identified between SEC and TC but there were trade-offs between these two ESs and WY.

SEC and WY had no direct interaction, forest and shrub land were shared drivers, and slope gradient, grassland and construction land were independent drivers. Shared and independent drivers provided leverage points for altering ES supply. Slope gradient and grassland had a dominant influence on SEC-WY trade-off in 2014. Quadratic function relationship can be found between slope gradient and trade-off, and there is a threshold point (15.16º) to minimize the trade-off. Moreover, reducing forest area and expanding grassland can restrain trade-off.

There is a unidirectional interaction between TC and WY (TC affect WY). Rainfall, grassland, farmland, and forestland are shared drivers. Rainfall and forestland aggravated trade-off but grassland can restrain it. Construction land is an independent driver, and forest and grassland proportions are dominant drivers affecting TC-WY trade-off in 2014 (a quadratic function relationship was found).

Considering the overall relationships among these three ESs, forest and grassland proportions need to be controlled at 20-30% and 45-60% respectively. We proposed the mode of ecological restoration, where small forest patches are inserted within a contiguous grassland matrix

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