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

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21

22 **Abstract**

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

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

44 watershed management, correlation analysis

45

46 **1. Introduction**

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

53 Landscape management has to balance the relationship between different ESs,
54 enhancing the synergies and weaken the trade-offs between them (Su et al., 2012a;
55 Tallis et al., 2008; Zheng et al., 2016; Zheng et al., 2014). A trade-off occurs when
56 enhancing one ES directly or indirectly decreases another ES, while a synergy occurs
57 when two or more ESs change in the same direction (Tomscha and Gergel, 2016).
58 Effective landscape management requires an understanding of the relationships
59 between different ESs (Yi et al., 2018) and in what situations trade-offs or synergies
60 would occur (Sun and Li, 2017). Therefore, a trade-off analysis of ESs is a key step in
61 landscape planning, management, and decision making (Darvill and Lindo, 2016;
62 Feng et al., 2017; Jia et al., 2014; Mach et al., 2015). Many studies have quantitatively
63 assessed and discussed the relationships of paired ESs using various methods.
64 Correlation analysis is one of the most commonly used approaches to do this (e.g.
65 Hou et al., 2017; Liu et al., 2019; Su and Fu, 2013; Sun and Li, 2017; Wang et al.,

66 2012; Wu et al., 2013; Xu et al., 2016; Zheng et al., 2016). Jiang et al. (2018)
67 combined correlation analysis and a constraint line approach to measure the complex
68 interactions amongst multiple factors associated with different ESs. Lü et al. (2014)
69 and Feng et al. (2017) used a trade-off index (root mean square deviation) to quantify
70 the trade-offs and synergies among different regulating services.

71 Land use is a significant factor associated with ES provisioning (Burkhard et al.,
72 2012; Dallimer et al., 2015; Kindu et al., 2016; Li et al., 2010; Liang et al., 2017; MA,
73 2005; Metzger et al., 2006; Zhao et al., 2006) . It is therefore important to quantify the
74 relationships between land use changes and the changes in ESs as these can support a
75 deeper understanding of the mechanisms associated with the enhancement of any
76 given ES and can provide useful guidance for potential future ecological restoration
77 strategies (Bryan, 2013; Foley et al., 2005; Zheng et al., 2014).

78 Changing land use through ecological restoration provides a critical corrective
79 intervention for addressing land degradation and contributes to the 2030 Global
80 Sustainable Development goal of Land Degradation Neutrality. The Chinese Loess
81 Plateau has been the subject of several ecological restoration programs and a number
82 of studies have reported the effects of restoration initiatives on ESs in this region.
83 Feng et al. (2013) and Xiao (2014) calculated the changes in carbon sequestration
84 since the Grain for Green program (GFGP), a large scale vegetation restoration
85 program, over a decade using remote sensing techniques and ecosystem modeling. Jia
86 et al. (2014) and Su et al. (2012a) evaluated the changes in multiple ESs in the
87 northern Shaanxi sub-region and quantified the trade-offs and synergies between

88 provisioning and regulating ESs using regression analysis. Pan et al. (2013)
89 established a measure of total ESs and used trade-offs indices to quantify changes in
90 the spatial distribution of multiple ES supply associated with different environmental
91 and land use factors in Jinghe watershed. A common feature of much previous
92 research is the lack of a temporal dimension in the evaluation of ESs interactions,
93 with simple changes in the spatial configuration of ESs being used to infer temporal
94 dynamics ('space-for-time' (Tomscha and Gergel, 2016) – see below), or analysis of
95 ES interactions over short time periods.

96 In land use planning, managers often aim to maximize one or several ESs
97 through landscape management. However, many ESs are not independent of each
98 other and frequently have highly non-linear relationships (Feng et al., 2017;
99 Rodriguez et al., 2006) over different temporal scales. Long-term ESs changes and
100 interactions are rarely studied, especially those across multiple time intervals
101 (Mouchet et al., 2014; Renard et al., 2015; Tomscha and Gergel, 2016). Ignoring
102 long-term trends makes it difficult to derive robust inferences about the impacts of
103 land use changes on the distribution and quality of some ESs (Dallimer et al., 2015;
104 Tomscha and Gergel, 2016). It is therefore important to quantify the long-term
105 impacts of changes in land use patterns and their impacts on the provision, quality and
106 spatial distribution of different ESs. Some studies have sought to incorporate
107 historical perspectives and time series data in their analysis of ES interactions.
108 Tomscha and Gergel (2016) compared 'space-for-time' and 'change-over-time'
109 approaches. The former uses changes in spatial relationships to infer dynamics over

110 time, while, the latter focuses explicitly on temporal changes. They found that the
111 space-for-time approaches can result in inconsistent characterizations of ES
112 correlations whereas an explicit focus on temporal change using time series data
113 analysis can support a deeper understanding of ES temporal relationships and their
114 dynamics. Dallimer et al. (2015) also identified time-series analysis and improved
115 understanding of historical ES dynamics and interactions as essential for ES
116 management. The need to examine the temporal dimension in detail, over a series of
117 time intervals, is because any evaluation of change may be significantly impacted by
118 one of environment event such as the extreme weather in a particular year (Bennett et
119 al., 2009; Li et al., 2017b). Additionally, changes in the patterns of ES interactions
120 observed at small temporal scales may be hidden at larger ones and the nature of ES
121 interactions may also change as environmental conditions change or in response to
122 new drivers (Renard et al., 2015). Consequently, it is important to examine the
123 temporal variability of ES relations over longer periods, with frequent temporal
124 sampling (Hein et al., 2016; Li et al., 2017b).

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

132 restoration at watershed scale.

133

134 **2. Research area**

135 The study area, Zhifanggou watershed (latitude 36°46'18"-36°43'13"N, longitude
136 109°14'01"-109°16'04"E), lies in the middle part of the Chinese Loess Plateau. The
137 total area is about 8.27 km² and elevations are 1030-1413m. It is characterized by
138 semi-arid climate and hilly-gully topography with thick loess coverage. The mean
139 annual temperature is 8.8°C, and the mean annual precipitation is 543mm, mainly
140 falling from June to September.

141

142 [INSERT FIG. 1 HERE]

143

144 The Zhifanggou watershed has been experienced a number of environmental
145 events and has been one of the areas selected for ecological restoration projects. For
146 these reasons it was identified as a suitable watershed to investigate the relationships
147 amongst ecological restoration, land use change and ES interactions. The soil of this
148 area is the typical loess soil and susceptible to erosion. Since the late 1930s, the
149 population has increased steadily and ongoing anthropogenic activities have
150 significantly changed the land use pattern and aggravated soil erosion processes (Li et
151 al., 2004). The amount of farmland increased rapidly with little consideration of
152 ecological impacts, resulting in severe soil erosion, landscape degradation and other
153 environmental problems. Consequently, a number of schemes to prevent soil erosion

154 have been initiated over past decades. Since the 1970s, soil and water conservation,
155 comprehensive watershed management and vegetation restoration have all been
156 implemented in this small watershed (Wang et al., 2012; Zhou and Liu, 2009). It was
157 also one of the pilot and demonstration areas for the GFGP which was implemented in
158 1999.

159

160 **3. Data and methods**

161 **3.1. Data resources**

162 In this study, multi-temporal data were assembled to investigate the LULC
163 changes at intervals during the period 1958 to 2015. Vector based maps of land use
164 were classified through the aerial photograph interpretation (API) at scales of 1:3500,
165 1:4500, 1:10000 and 1:10000, taken in February 1958, May 1978, June 1990 and June
166 1995, respectively (Fu et al., 2006). Prior to the API, a land use reconnaissance survey
167 was carried out to obtain a general understanding of the land use situation of the study
168 area (Fu et al., 2006). Other data for 2000, 2005, 2010 and 2015 were generated
169 through interpretation of combined Landsat TM and Google Earth images. The LULC
170 was classified into six categories: farmland, woodland, grassland, water, artificial
171 surfaces and unused land and linked to data on climate, topology and soil type to
172 calculate different ESs. The details and sources of these datasets are listed in Table
173 A.1.

174

175 **3.2. Estimation of ESs**

176 The following six ESs were calculated for each of the eight time points (1958,
177 1978, 1990, 1995, 2000, 2005, 2010 and 2015): food provisioning, soil retention,
178 carbon sequestration, hydrological regulation, water purification and habitat
179 provisioning for biodiversity. They were selected because of their relevance to current
180 and future management and decision-making. The following subsections describe
181 how they were calculated.

182 **3.2.1. Food provisioning**

183 Food provisioning is an important type of provisioning service and agricultural
184 production plays a significant role in guaranteeing local incomes, livelihood and
185 economic development. Crop yield (CY) was chosen as the indicator of this service.
186 The data was obtained from existing publications (Zhang et al., 1998; Zhou and Liu,
187 2009) and the yearbooks of the Yan'an municipality that covers the study area.

188 **3.2.2. Soil retention**

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

$$191 \quad SR = RKLS - USLE = R \times K \times LS - R \times K \times LS \times C \times P = R \times K \times LS \times (1 - C \times P)$$

192 where SR is the amount of annual soil retention ($\text{t ha}^{-1} \text{ yr}^{-1}$), a measure of the gap
193 between potential and actual soil erosion; $RKLS$ is the potential soil loss with no
194 vegetation coverage or support practice ($\text{t ha}^{-1} \text{ yr}^{-1}$); $USLE$ is the annual soil loss (t
195 $\text{ha}^{-1} \text{ yr}^{-1}$); R is rainfall erosivity, from daily rainfall (MJ mm ha^{-1}) data (Richardson et
196 al., 1983); K describes a soil erodibility factor ($\text{t h MJ}^{-1} \text{ mm}^{-1}$), set with reference to
197 Fu (2005); LS is a slope length and steepness factor calculated using the method

198 developed by Desmet and Govers (1996) for two-dimension surfaces; C is a cover and
199 management factor computed according to the approach described in publications
200 relevant to the Chinese Loess Plateau (Fu et al., 2005; Hu et al., 2014; Li et al., 2014;
201 Liu and Fu, 2016; Pang et al., 2012; Wei et al., 2002). The C values for different
202 LULC are shown in Table A.2. P is the support practice factor, which corresponds to a
203 slope gradient factor for farmland ($P = 0.2 + 0.03\theta$, where θ is slope (%)) and set to
204 1 for all other land use types (Fu et al., 2005).

205 **3.2.3. Hydrological regulation**

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

220 (farmland, grassland and woodland) and root depth was extracted from Bao (2015).

221 **3.2.4. Carbon sequestration**

222 Carbon sequestration is a key regulating service. It is often represented by net
223 primary productivity (NPP) in the literatures (Jiang et al., 2016; Li et al., 2017b; Lü et
224 al., 2012; Ribaudó et al., 2016). In this study, information on this service was
225 generated from multi-temporal measures of Soil Organic Carbon (SOC). SOC values
226 from 1958 to 1978 were derived from soil survey maps from Shaanxi Province Soil
227 Survey Office. SOC has been sampled directly since the 1990s in the watershed with
228 average values for each LULC class allocated for the period 1990 to 1995 according
229 to existing publications (Chen et al., 2010; Zhang and Chen, 2010; Zheng, 1996).
230 SOC values from 2000 to 2015 were determined according to values given in the
231 literatures (Cao, 2013; Geng et al., 2014; Li et al., 2013; Li, 2013; Liang et al., 2013;
232 Liang, 2011; Liu, 2015; Lü and Liang, 2012; Wang et al., 2002; Xu, 2003; Zhang et
233 al., 2013) and from the spatially distributed NPP values. NPP was estimated using the
234 Carnegie-Ames-Stanford Approach (CASA, Potter et al., 1993), as follows: $NPP =$
235 $APAR \times \varepsilon$, where NPP is the monthly net primary productivity (gC m^{-2}); $APAR$ is the
236 canopy-absorbed incident solar radiation (MJ m^{-2}), and ε is the light utilization
237 efficiency (gC MJ^{-1}), which is determined by temperature and precipitation.

238 **3.2.5. Habitat provisioning for biodiversity**

239 Biodiversity is closely linked to many ESs. Patterns of biodiversity are inherently
240 spatial and operate over different scales. They can be estimated by analyzing maps of
241 LULC together with land uses that are habitat threats. Habitat quality (HQ) can be

242 used as a proxy for habitat for biodiversity provisioning as it relates to the capacity of
243 ecosystem to provide suitable environments for living organisms (Hou et al., 2017). A
244 HQ index (dimensionless with a relative value 0-1) was calculated using the InVEST
245 model from LULC habitat and biodiversity threat data. The key step is to determine
246 which LULC classes support habitat biodiversity, the sensitivity of these habitats to
247 potential threats (Sharp et al., 2016), the importance or weight of each threat and its
248 persistence across spatial distances. Habitats were classed into woodland, grassland,
249 farmland and water. The threats were framed as LULC transitions to farmland,
250 artificial area and unused land. The threat values were assigned according to the
251 published research (Chen et al., 2016; Du and Rong, 2015; Gao et al., 2016; Jing,
252 2016; Liu, 2014; Wang, 2016; Xiao, 2011; Zhong and Wang, 2017; Zhu, 2012) and
253 are shown in Table A.2.

254 **3.2.6. Water purification**

255 As well as soil retention and climate (hydrological) regulation, water purification
256 is a crucial regulating service in arid and semi-arid area. Water quality (WQ) was
257 calculated by the InVEST Nutrient Delivery Ratio model to provide an indicator
258 measure of the level of water purification. The model does not capture the detail of
259 the nutrient cycle but rather simulates the long-term, steady-state flow of nutrients
260 through empirical relationships (Sharp et al., 2016). The main parameters are the
261 nitrogen loading and maximum retention efficiency for each land use type, and the
262 distance after which it is assumed that a patch of LULC retains nitrogen at its
263 maximum capacity (Sharp et al., 2016). These empirical parameters were extracted

264 from recent publications (Han et al., 2016; Huang, 2014; Pan, 2016; Wu et al., 2017;
265 Xiao, 2013) and are displayed in Table A.2.

266 **3.3. Trade-off and synergy analysis**

267 **3.3.1. Correlation analysis**

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

$$273 \quad ES_{std} = (ES_{est} - ES_{min}) / (ES_{max} - ES_{min})$$

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

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

286 ArcGIS 10.2) and standardized to quantify the correlation coefficients. In general,
287 climatic and land use changes were found to be the major drivers of the fluctuations in
288 ESs (Bateman et al., 2013; Fu et al., 2017; Schroter et al., 2005), especially for those
289 related to hydrological regulation and soil retention (Jiang et al., 2016; Pan et al.,
290 2013; Su and Fu, 2013) as they typically vary with rainfall (Fig. A.2), which may
291 conceal the influence of any LULC change. Thus mean annual rainfall (543mm) was
292 considered to be uniform across such a small watershed and used as an input to
293 calculate these ES indicators and to capture the impacts of land use changes on ESs.
294 The Pearson correlation coefficients between pairs of ESs were calculated using SPSS
295 22.0.

296 3.3.2. Root mean square deviation

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

$$299 \text{RMSD} = \sqrt{\frac{1}{n-1} \times \sum_i^n (ES_i - \overline{ES})^2}$$

300 where ES_i is the standardized value of ES i , and \overline{ES} is the expected value of the i
301 number ES . In brief, it extends the meaning of trade-off from negatively correlated
302 relationships to the inclusion of uneven rates of same-direction change between ESs
303 (Lü et al., 2014). In other words, even when a synergistic relationship between the
304 two ESs is present, it may be tendentious with the effect that an increment of one
305 service is likely to an uneven increase in the other. It is a simple but effective way to
306 represent the degrees of trade-offs between any two or more ESs, no matter how they

307 are correlated to each other (Lü et al., 2014). This measure also supports decisions
308 and choices over more suitable synergistic LULC types (i.e. with smaller RMSD
309 values). More details and illustrations of the trade-offs between two ESs through
310 RMSD is provided in Bradford and D'Amato (2012) and Lü et al. (2014).

311

312 **4. Results and discussions**

313 **4.1. Policy-driven vegetation restoration and associated land use change is the** 314 **major driver for ES change**

315 **4.1.1 Land use and land cover under policies implement**

316 The percentage of each LULC class in different periods is shown in Fig. 2(a). In
317 1958, the main LULC classes were grassland and farmland, which accounted for
318 31.78% and 56.34% of the watershed, respectively. In 2015, woodland, grassland and
319 farmland accounted for 52.43%, 36.31% and 10% of the watershed, respectively. The
320 main land use changes over the past half century, therefore, were significantly
321 increased woodland and reduced farmland. Another LULC change was the decrease in
322 unused land from 10.63% to 0%. There are some slight fluctuations in grassland
323 around a stable level. Little variation can be seen in water and artificial surfaces (both
324 within 0.5%).

325

326 [INSERT FIG. 2 HERE]

327

328 The LULC transfer matrix in Table A.3 indicates that the changes in LULC were

329 not simply transitions from farmland and unused land to woodland. The main LULC
330 conversions were from farmland to woodland (54.05% of the 1958 area) and
331 grassland (30.62%), from grassland to woodland (54.88%), from artificial surfaces to
332 woodland (28.94%) and from unused land to woodland (54.97%) and grassland
333 (39.17%). The locations of these overall changes are shown in Fig. A.3.

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

347

348 **4.1.2. Variations of ecosystem services**

349 Based on the above methods (Section 3.2), values for each ES indicator were
350 calculated (see Table A.4) and standardized ES indicators are shown in the radar

351 graphs (Fig. 3) for each of the eight time periods. The values of several ES indicators,
352 CY, SR, HQ and WQ, increased continually over the whole period, peaking around
353 2000. SOC decreased initially (1958 - 1990) and then increased to 2015. Conversely,
354 there was a downward trend in the WY over study period. The radar graphs show that
355 changes in these mainly happened during 1978-2000 corresponding to the observed
356 LULC changes. Many of the ES indicators improved through land use changes driven
357 by ecological restoration projects, but the increased water use associated with
358 vegetation restoration resulted in a significant decrease on water yield.

359

360 [INSERT FIG. 3 HERE]

361

362 **4.1.3. The major driver is the policy rather than climate change**

363 Changes in climate and policy are two important factors that influence the ES
364 provisioning. The trends and changes of the two main climatic variables, precipitation
365 and temperature, during the last half century are shown in Fig. 4. Annual average
366 rainfall showed a non-significant negative trend (slope=-0.467, $R^2=0.0049$, $P=0.58$).
367 Mean annual rainfall was used to calculate WY and SR with the implication that
368 precipitation has little influence on the results. Fig. 4 shows that there is a significant
369 positive trend for annual average temperature (slope=0.033, $R^2=0.589$, $P=8.66\times 10^{-14}$).
370 Temperature is one factor for reference evapotranspiration in WY. Using the climatic
371 factors of 1958, water yield was calculated under different LULC scenarios
372 (1978-2015) to evaluate their contribution to this ES (Fig. 5). Land use change makes

373 an important contribution to decreasing WY and its effects are greater than climatic
374 factors under uniform rainfall, especially after ecological restoration. Thus
375 temperature is not a key factor associated with ES change.

376

377 [INSERT FIG. 4 HERE]

378 [INSERT FIG. 5 HERE]

379

380 There is an obvious chain of policy implementation, leading to land use change,
381 leading to ES changes. The Zhifanggou watershed witnessed a series of significant
382 historical events. Before the 1930s few people lived in the area and the population has
383 increased steadily since then (Fu et al., 2006; Zhang et al., 2004). In the 1950s, policy
384 encouraged farming and the felling and clearing of natural vegetation for fuel. At that
385 time individuals were less aware of and concerned with the regulating and supporting
386 environmental protection services in their pursuit of provisioning services such as
387 food and fuel. Because of rapid population growth and low yields, more and more
388 land was used to produce grain and natural vegetation was destroyed, leading to
389 increased and severe soil erosion. This reduced land fertility and more land had to be
390 converted to agriculture from natural vegetation to sustain population growth. Thus
391 during this period the land use structure in the watershed was subject to a number of
392 pressures. To alleviate this and to increase net grain yields and to reduce the pressure
393 on farming, policy at the national level distributed land use rights to individual
394 farmers through the introduction of the Household Responsibility System and

395 controlled population growth by implementation of the Family Planning Policy in
396 1978. In the early 1980s, the Chinese government initiated watershed soil and water
397 conservation programs by constructing terraces and check-dams or by planting
398 non-agricultural vegetation on steep slopes (Fu et al., 2006; Su et al., 2012a; Zhang et
399 al., 2004). Zhifanggou experienced large changes in LULC and associated ESs with
400 the increases of woodland and decreases of farmland. The GFGP is the largest
401 ecological restoration program in China and the Zhifanggou watershed was part of the
402 pilot project during the first phase of the GFGP in 1999 (Hou et al., 2017; Lü et al.,
403 2015). This explains the increase in woodland from 1978 to 1990 and from 1995 to
404 2000.

405 The results of this study show several major changes in ESs after vegetation
406 restoration policies. Although the area of farmland shrunk significantly after 1978,
407 food provisioning is influenced by not only cropland area but also technological and
408 economic developments, which increased yields and the diversity of grain species.
409 For hydrological regulation, dramatic decreases occurred after two phases of
410 ecological restoration, mainly associated with increases in woodland which increases
411 evapotranspiration and leads to water shortages (Jackson et al., 2005; Li et al., 2017b).
412 However, water yield is an important resource, supporting ecosystem functioning,
413 human life and agricultural production (Zheng et al., 2016). Understanding this
414 balance between different water related ESs has been a critical development in recent
415 research. Feng et al. (2016) noted that the Loess Plateau is approaching its sustainable
416 water resource threshold when the demands from vegetation restoration and human

417 society are considered. Additionally, since different LULC types support distinctive
418 ESs, both water purification and habitat quality were found to increase dramatically
419 after the implementation of ecological restoration programs. This reinforces the
420 functional chain of “policy implementation-land use change-ES change”. Similar
421 chains have also been observed in studies in other countries (e.g., Arunyawat and
422 Shrestha, 2016).

423

424 **4.2. Grassland is a more suitable for ecological restoration in drylands**

425 In order to understand the temporal variation in ESs, the percentage change for
426 each ES indicator was calculated for each of the 7 time intervals (Fig. 6). Two periods,
427 1978-1990 and 1995-2005, witnessed a significant increase in food provisioning and a
428 decrease in farmland area. Although the area of cultivated land decreased, the unit
429 area grain yield increased significantly. Carbon sequestration fluctuated greatly during
430 the whole period showing a decline at first and then large increases. There are three
431 points deserving more attention. Firstly, soil retention increased continuously from
432 1958 to 2000 but the degree of increment remained almost even. That is to say,
433 increased woodland under the implementation of ecological restoration
434 (comprehensive watershed management and GFGP) didn't dramatically increase soil
435 retention. Secondly, a general decreasing trend can be seen for water yield over the
436 whole period, especially after the GFGP (1995-2000). Finally, the improvements of
437 HQ and WQ mainly occurred during the periods of 1978-1990 and 1995-2000, which
438 were the main periods for woodland increment. However, the increases in HQ after

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

441

442 [INSERT FIG. 6 HERE]

443

444 To further investigate these findings, root mean square deviation (RMSD) of
445 paired ESs in different land use types was used to better understand the changes in ES
446 trade-offs (Fig. 7). Overall, the RMSDs among all paired services (except for HQ-WQ)
447 are lower for grassland than for woodland. This indicates that the ESs provided by
448 woodland may be more tendentious and uneven. Grassland acts as a recovery measure
449 with much smaller RMSD and therefore may support a greater level of synergistic
450 ESs. Similar findings have been noted by other studies in the Loess Plateau (Li et al.,
451 2017b; Pan et al., 2013).

452

453 [INSERT FIG. 7 HERE]

454

455 **4.3. Long-term monitoring and assessment are critical for understanding the**
456 **variability of complex ESs interactions**

457 **4.3.1. Changes in relationships between paired ESs**

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

461 2014) over the 40 sub-catchments. The coefficients of the spatial distribution of two
462 ESs were derived from environmental gradients, spatial patterns of vegetation or
463 LULC. They reflect a static correspondence relationship with positive values
464 indicating that the spatial distributions of both ESs are consistent (both ESs display a
465 higher or lower value at the same time) (Zheng et al., 2014). The correlation
466 coefficient for multiple temporal intervals over a long period characterize the dynamic
467 interaction between ESs and the relationships between them and LULC.

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

475

476 [INSERT TABLE 1 HERE]

477

478 The temporal correlation coefficients for each pair of ES indicators are listed in
479 Table 2. These were calculated over the 40 sub-catchments (under the average rainfall)
480 over paired time intervals. Positive values indicate that the two ES indicators changed
481 in the same direction and that a synergy may exist between them, and negative values
482 infer a trade-off (Zheng et al., 2014). Over the past half century some pairs of ES

483 indicators, such as SR-WY, WY-SOC, WY-HQ and WY-WQ showed varying
484 directional trends and degrees of correlation. Another surprising trend is that all
485 coefficients were positive from 1990 to 1995, regardless of relationship was before or
486 after the period.

487

488 [INSERT TABLE 2 HERE]

489

490 **4.3.2. Long-term monitoring and assessment are basic and critical tools**

491 Long-term data provide the temporal perspective needed to identify the
492 underlying thresholds of ES change on for future planning. The spatial and temporal
493 interactions among paired ESs reveal that interactions are not temporally fixed. This
494 highlights the need to consider the temporal dynamics of ESs and their drivers over
495 long periods to better understand the trade-offs and synergies among multiple ESs,
496 especially during ecological restoration activities (Li et al., 2017a). Both spatial and
497 temporal correlation analysis of the 40 sub-catchments over 8 time periods in this
498 research identified major changes in relationships between pairs of ESs before 1990
499 and after 1995. Greater temporal synergies were found between 1990 and 1995 with
500 positive values of ES indicators (Table 2). Considering these findings alongside those
501 from previous research (Li et al., 2017b; Pan et al., 2013) and the area of each LULC
502 at that period (Section 4.1.1), a ratio of grassland to woodland of around 1.5 for the
503 Zhifanggou watershed could support more synergies between ESs. Of course, it is
504 important to guarantee both food yield and security and to ensure suitable locations

505 for different LULC types. However, if this finding is correct then low ES indicator
506 values can be improved in other ways. For example, WQ and CY could be increased
507 with advanced agricultural technology and SOC could be accumulated with the
508 growth and soil retention of vegetation. The ratio, therefore, is an important reference
509 for future research in similar watersheds in the Loess Plateau and other arid and
510 semi-arid areas. Assessment of long-term data provides the basis for identifying the
511 dynamics of ES interactions and to suggest future planning strategies to achieve this
512 ratio.

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

525 The fifteenth of the seventeen goals for sustainable development presented by
526 the United Nations refers to achieving a land degradation-neutral world by 2030. In

527 order to achieve this goal, monitoring land status is a fundamental and key component
528 (Grainger, 2015; Sietz et al., 2017; Tal, 2015) of any analysis which should also
529 include multiple indicators such as soil properties (Toth et al., 2018) and land
530 productivity (Cowie et al., 2018). Changes in LULC, ESs and their relationships
531 should be monitored and assessed over long periods in order to support the
532 development and iterative refinement of land use planning and management. Renard
533 et al. (2015) and Tomscha and Gergel (2016) also suggested that the ES relationships
534 should be recognized and included as part of long-term monitoring of ESs. A
535 long-term national or even global network of monitoring should be encouraged (Luo
536 et.al, 2018; Safriel, 2017) to monitor potential land degradation over time and its
537 impacts on ESs to inform management activities (Renard et al., 2015).

538 **4.4. Limitation from data sources and models**

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

545 The identification and classification of LULC are also possible sources of
546 uncertainty. The broad categories used to interpret the remote sensing image will
547 result in the loss of potentially important information. For example, if all woodlands
548 are regarded as one LULC class, coarse estimates on soil retention, water penetration

549 and evapotranspiration, or NPP may be expected if the impacts of some detailed
550 features such as forest age, forest canopy coverage, and species composition are not
551 considered. Inevitably the degree of detail is limited by the source data and the
552 comparatively long temporal scale in the present research.

553 Uncertainties are also present in the assessment of ES indicators using models.
554 Firstly, several factors affect the accuracy of annual WY estimates. Although the
555 results of evapotranspiration modeling were considered to be much closer to reality
556 than the results obtained from the remote sensing based product (MODIS-ET), other
557 uncertainties also arise (Lü et al., 2012): (1) changes in water storage should not be
558 negligible for wet years; (2) water resources are used by communities and are affected
559 by soil conservation structures (e.g., check dams); and (3) there will be differences in
560 water demand for vegetation with different species and in restoration years. Secondly,
561 the estimation of SR was undertaken through the application of the USLE, which is
562 based on a statistical relationship established from a large number of plot scale
563 rainfall-erosion experiments (Ciesiolka et al., 2006; Kinnell, 2008). It estimates rill
564 and interrill soil detachments on hill slopes from rainfall, soil and soil cover
565 parameters, and management factors (Tattari and Barlund, 2001). Therefore, it is a
566 suitable method to estimate the effect of hill slope vegetation rehabilitation on soil
567 conservation. However, this may have been overestimated in this research due to the
568 omission of the local sediment deposition process (Kinnell, 2008) and the use of
569 degraded bare ground as control (Zhang et al., 2017). These overestimations were
570 made for the absolute values of annual SR but did not exclude the SR brought by

571 vegetation rehabilitation. Uncertainties also arose in the estimation of input
572 parameters for the USLE (Tattari and Barlund, 2001). To reduce this, parameters
573 experimentally established and verified in the Loess Plateau region were used for
574 estimating the different factors in the USLE (Fu et al., 2011; Liu and Fu, 2016; Lü et
575 al., 2012; Su and Fu, 2013; Su et al., 2012b). Similarly, uncertainty reduction in
576 modeling HQ and WQ was through using experiential parameters reported for the
577 Chinese Loess Plateau as much as possible.

578

579 **5. Conclusions**

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

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

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

601

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608

609 **Appendices**

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

612

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888 Lists of Figs. 1-7:

889 Fig. 1 Location and photos of Zhifanggou watershed.

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

892 Fig. 3 Radar graph of the standardized ES indicators for each time period between
893 1958 and 2015.

894 Fig. 4 Time series of (a) annual precipitation and (b) mean annual temperature during
895 1951-2015.

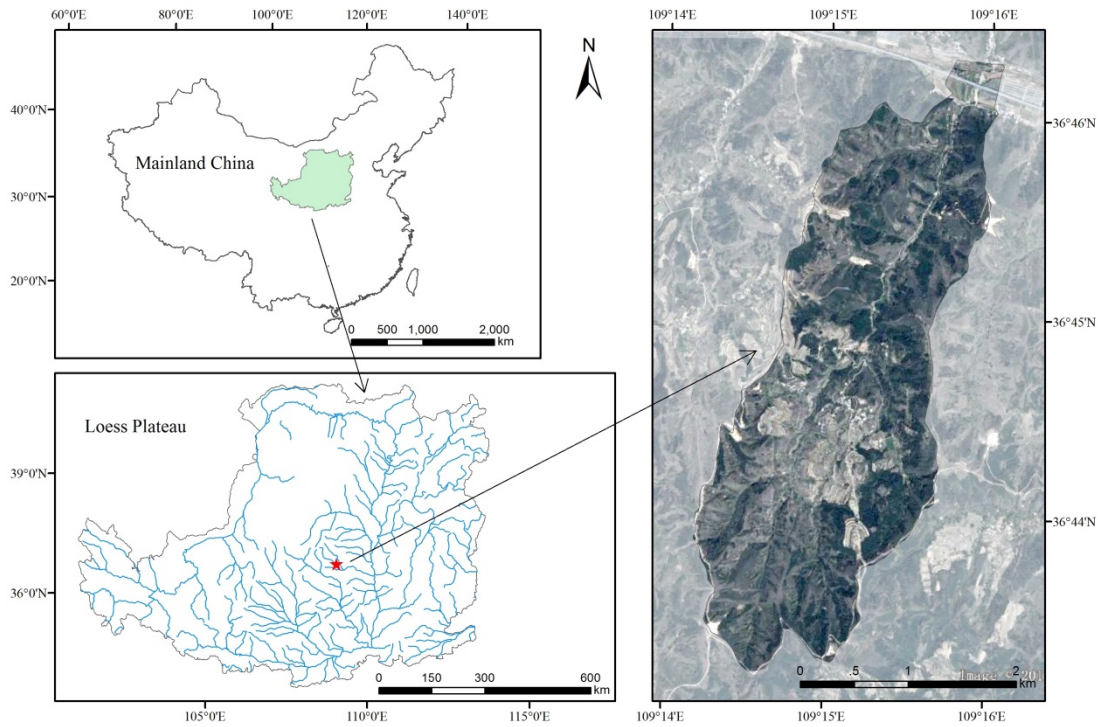
896 Fig. 5 The effect of LULC and climatic factors on water yield.

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

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

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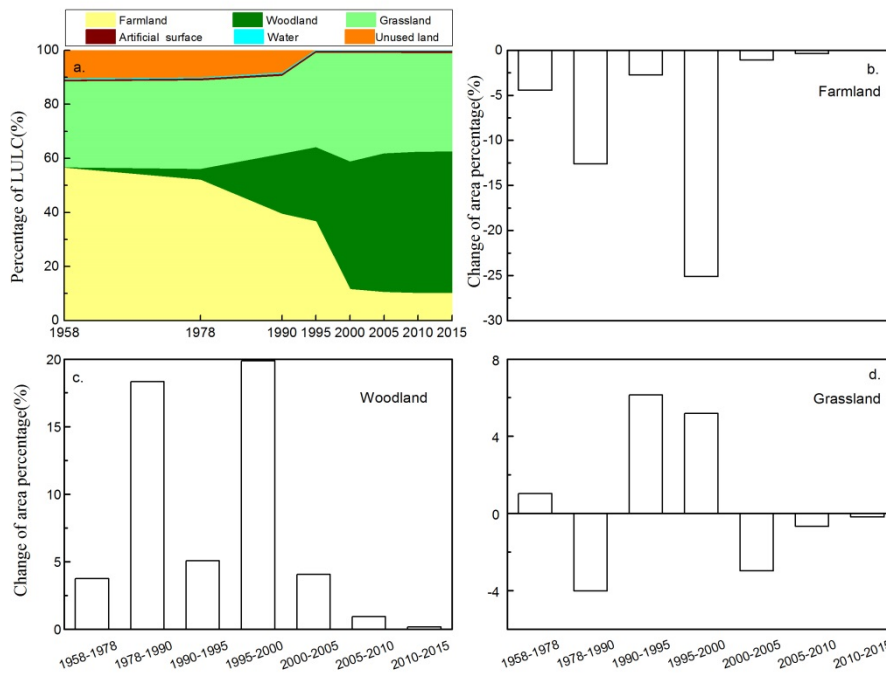
902 **Fig. 1.** Location and photos of Zhifanggou watershed. a: the location of Zhifanggou

903 watershed in Chinese Loess Plateau with a Google Earth image of the study area on

904 the 25th of July, 2015. b: three photos taken during a field survey of the watershed in

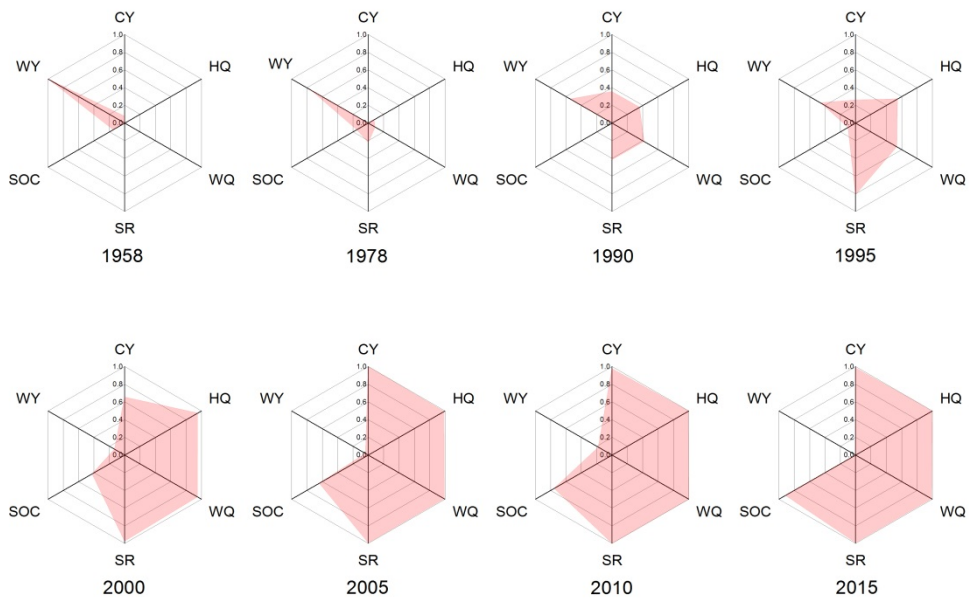
905 May of 2017.

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

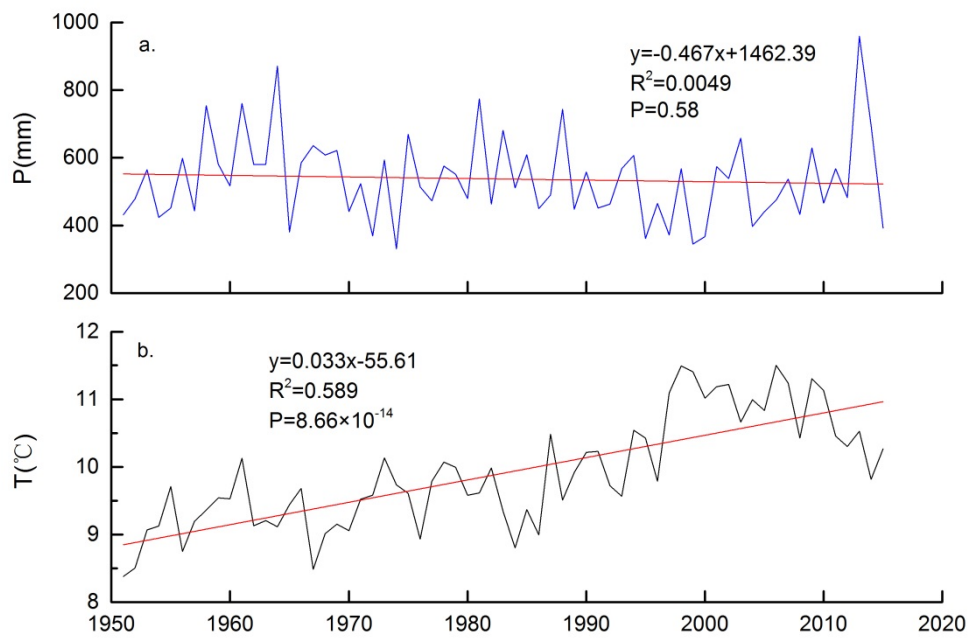
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914 **Fig. 3.** Radar graph of the standardized ES indicators for each time period between
915 1958 and 2015. CY is crop yield, SR is soil retention, WY is water yield, SOC is soil
916 organic carbon, HQ is habitat quality and WQ is water quality.

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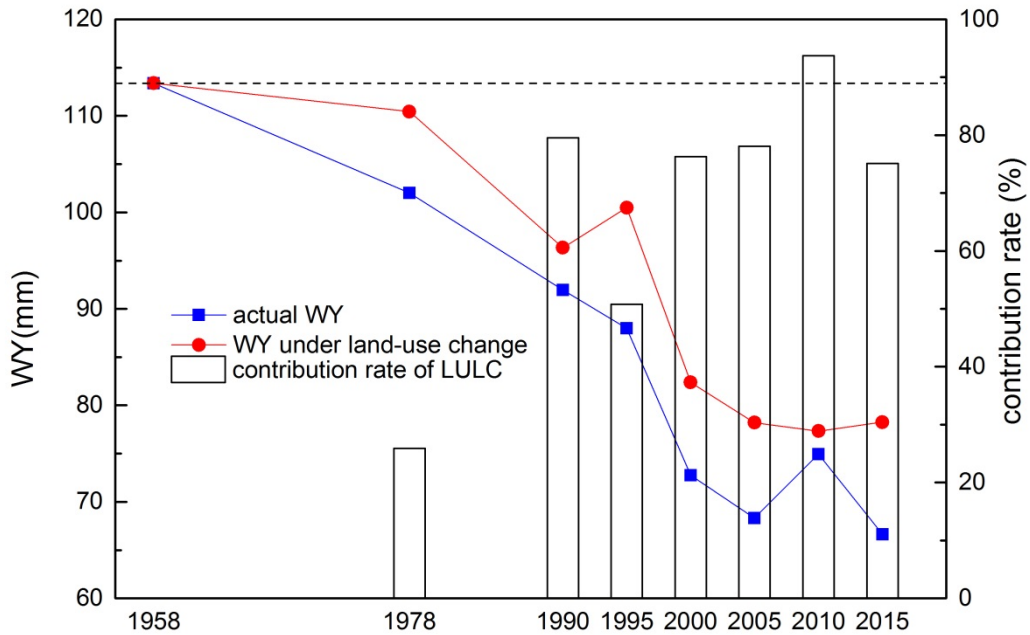


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919 **Fig. 4.** Time series of (a) annual precipitation and (b) mean annual temperature during

920 1951-2015.

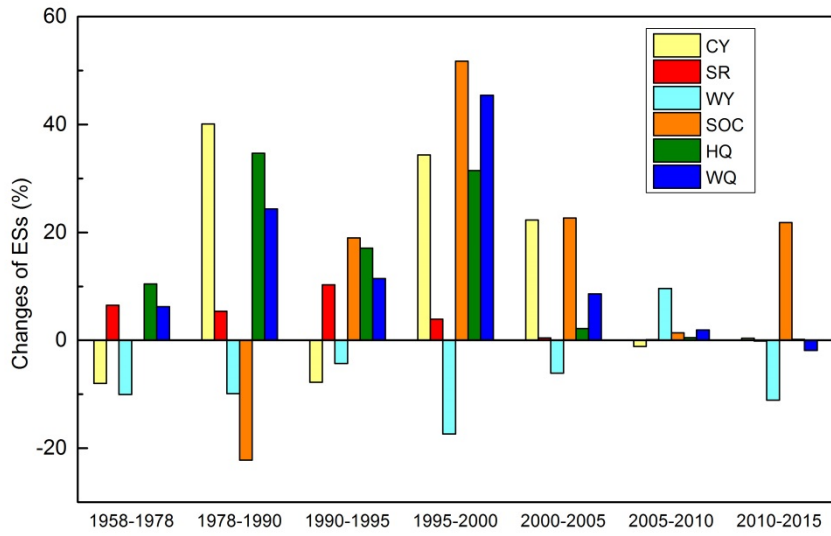
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924 **Fig. 5.** The effect of LULC and climatic factors on water yield. The change of water
 925 yield (WY) driven by LULC (red line) and by both LULC and other climatic factors
 926 under average annual precipitation (543mm) (blue line), with the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

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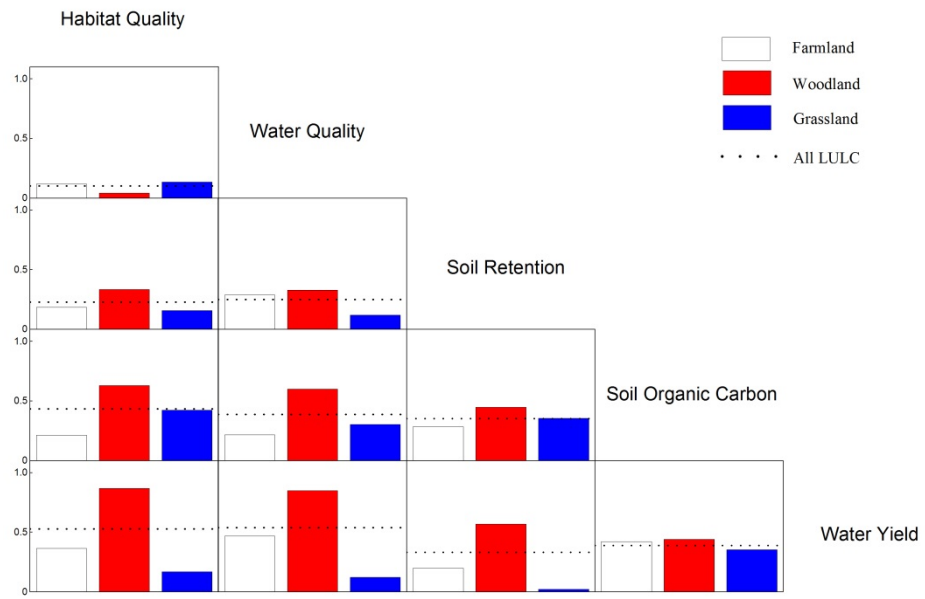
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932 **Fig. 6.** Percentage changes of ES indicators over each paired time period. CY is crop

933 yield, SR is soil retention, WY is water yield, SOC is soil organic carbon, HQ is

934 habitat quality and WQ is water quality.

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

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942 Lists of Tables 1-2:

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

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

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946 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**

947 Blue and red numbers represent significantly positive and negative correlations,

948 respectively (* indicates $p < 0.05$; ** $p < 0.01$; No * $p \geq 0.05$). CY is crop yield, SR is

949 soil retention, WY is water yield, SOC is soil organic carbon, HQ is habitat quality

950 and WQ is water quality.

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952

953 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

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

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