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***Highlights (for review)**

Highlights

- ES bundle framework quantifies landscape scale ES tradeoffs or synergies changes.
- Most of the ecosystem services were improved as a result of restoration programme.
- The synergies among ecosystem services were weakened while gaps were more evident.
- Baseflow is a sensitive indicator as the response to the vegetation restoration.
- Bundles can capture the changed interactions of ecosystem services.

Bundling ecosystem services for detecting their interactions driven by large-scale vegetation restoration: enhanced services while depressed synergies

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1 **Abstract**

2 Ecosystem service (ES) bundles can facilitate comprehensive understanding of
3 the spatial configurations and interactions of multiple ESs across large-scale
4 landscapes. They are critical for informing policy and improving ecosystem
5 management. The spatial dimension of ES bundles has been addressed in recent
6 research but little work has considered the temporal changes of ES bundles. This
7 paper uses a case study in the Loess Plateau, the core area of vegetation restoration in
8 China, to explore changes in ES spatial distributions, bundle types and multiple ES
9 interactions in a period of rapid vegetation restoration between 2000 and 2015.
10 Measurable proxies, biophysical indicators and the InVEST model were used to
11 quantify 10 ESs. We found that (1) most of the ESs were improved, especially
12 provisioning services and carbon sequestration. (2) There is a steady tradeoff between
13 provisioning services and most regulating services, while the impacts of vegetation
14 restoration on agricultural production were small. (3) The synergies among ESs were
15 weakened, implying the presence of subtle functional ES interdependencies. (4)
16 Changes in the bundling patterns between 2000 and 2015 revealed heightened gaps
17 among ESs due to the upsurge of carbon sequestration and deterioration of the
18 baseflow regulation. This research provides a new perspective for understanding the
19 interactions between multiple ESs with regional vegetation restoration activities.
20 Ecological restoration programmes play an important role in enhancing ESs, but they
21 may also lead to expanded gaps between ESs. Baseflow regulation could be included
22 as a key indicator to support a comprehensive understanding of the impacts of
23 restoration interventions. The ES bundle framework is able to capture changes over
24 time of the ES interactions across a large-scale landscape and facilitates informed ES
25 management.

26 **Keywords:** Ecosystem service bundles; Temporal change; Synergies and trade-offs;
27 Ecological restoration; Regional scale

28 **1. Introduction**

29 Ecosystem services (ESs) are valuable tools for landscape planning and
30 management as they support understanding of natural resource value by stakeholder
31 groups and decision makers (Queiroz et al., 2015). Recently, incorporating multiple
32 ESs into local or regional land-use planning is considered as an essential step to
33 mainstream ESs, which should focus on associations among ESs (De Groot et al.,
34 2010; Goldstein et al., 2012). Associations among ESs are commonly referred to ES
35 interactions as changes in one service may alter the provision of another (Bennett et
36 al., 2009; Raudsepp-Hearne et al., 2010). Such interactions depend on whether the
37 presence of one ES excludes others, or whether multiple ESs are able to coexist and
38 be enhanced by each other simultaneously. These interactions are, consequently,
39 represented mainly in the form of trade-offs and synergies (Rodriguez et al., 2006).
40 There are diverse relationships between individual ESs and they can exhibit different
41 patterns across large-scale landscapes. Yet, explicit information, guidance and
42 methods for understanding the interactions among multi-ESs across heterogeneous
43 landscapes remains limited (Qiu and Turner, 2013). And recent research has
44 advocated the need for generic frameworks to be developed to facilitate the
45 management of ES interactions and to delineate their complex relationships (Spake et
46 al., 2017).

47 One such framework is the concept of ES bundles (Raudsepp-Hearne et al.,
48 2010). These describe temporally or spatially consistent associations, tradeoffs and
49 synergies among sets of services and can be used to delineate areas supplying similar
50 ES magnitudes and combinations within a landscape (Raudsepp-Hearne et al., 2010).
51 This allows related ESs to be treated together as related entities and to be represented
52 geographically (Turner et al., 2014). Initial work by Raudsepp-Hearne et al. (2010)
53 demonstrated that ES bundles could allow critical trade-offs and synergies to be
54 predicted. Later work over various spatial scales used the bundles framework to
55 examine their interactions (Crouzat et al., 2015; Derkzen et al., 2015; Kong et al.,
56 2018; Turner et al., 2014). These focused on delineating the ES bundle distribution to
57 facilitate understanding of ES associations and their underlying social-ecological

58 drivers, and for communicating the potential impacts of management decisions to
59 policy-makers (Spake et al., 2017).

60 However, ES interactions are not static and any spatial or temporal changes in
61 ESs may not be reversible in the future (Howe et al., 2014; Hou et al., 2017). Thus
62 evaluating the dynamic of ES interactions is crucial for managing ESs to avoid
63 potentially undesirable trade-offs. Understanding ESs interactions across temporal
64 scales, therefore, is another key challenge (Mouchet et al., 2014). In particular,
65 intensive human activities, both positive and negative, have increasingly changed the
66 structure and function of ecosystems, and thus deeply affected the ES interactions
67 (Qiu and Turner, 2013). In this context, widespread ecological restoration
68 programmes across the globe can be considered as a positive interventionist activities
69 towards achieving the major goals of restoring regional ESs and enhancing
70 biodiversity (Clewell and Aronson, 2013). Quantifying the changes among multiple
71 ESs in restoration areas plays an important role in understanding their trade-offs and
72 synergies, and provides insights into the effects of restoration activities, contributing
73 to better landscape management. However, as yet few studies have explored how
74 multiple ESs change in restoration processes in response to such seemingly positive
75 human intervention activities. Thus, applying the framework of ES bundles, the
76 purpose of our study is to tackle this deficiency to detect how certain ESs bundled and
77 changed during regional vegetation restoration process.

78 Benefits arising from land management interventions and natural ecosystem
79 protection, including increased agricultural outputs and enhanced ecological
80 conditions have been detected at the national level in China, (Bryan et al., 2018). The
81 Loess Plateau in China has experienced significant vegetation restoration since the
82 implementation of Grain to Green Programme (GTGP: a national programme of
83 revegetating sloping cropland). This has had impacts on ecosystem structure and
84 function, as well as on the supply and delivery of ESs. Recent studies in the Loess
85 Plateau have mainly focused on the responses of vegetation, soil or water-related ESs.
86 Feng et al. (2013) evaluated the changes in carbon sequestration and found that the
87 ecosystems in the Loess Plateau had shifted from a net carbon source in 2000 to a net

88 carbon sink in 2008 owing largely to the impact by the GTGP. The soil erosion
89 control service of regional ecosystems was also significantly improved during the
90 same period (Fu et al., 2011). Some research has also suggested a reduction of runoff
91 during this period (Li et al., 2016; Liang et al., 2015). Moreover, the interactions
92 among different ESs were explored to provide practical criteria for land use
93 policy-making. Tradeoffs and synergies were often found between water yield and
94 soil retention/carbon sequestration, and between soil retention and carbon
95 sequestration, respectively (Su and Fu, 2013). The constraining effects of rainfall have
96 also been detected along with tradeoffs or synergies among carbon sequestration, soil
97 retention, and hydrological regulation (Jiang et al., 2018).

98 Informed by the above literature, this study uses ES assessment and bundling
99 analysis in the Loess Plateau, as a typical regional case study. It seeks to uncover ES
100 interactions and their variations across space and time as driven by regional
101 vegetation restoration activities. More specifically, we propose the following
102 questions: (i) how does the supply of multiple ESs change? (ii) How do the trade-offs
103 and synergies between ESs change? (iii) Are these ESs always bundled together or are
104 there changes in each cluster and their spatial distribution? To address these questions,
105 we mapped spatial patterns of ten ESs across the Loess Plateau in 2000 and 2015, and
106 explored the changes of ES associations using the ES bundle framework.

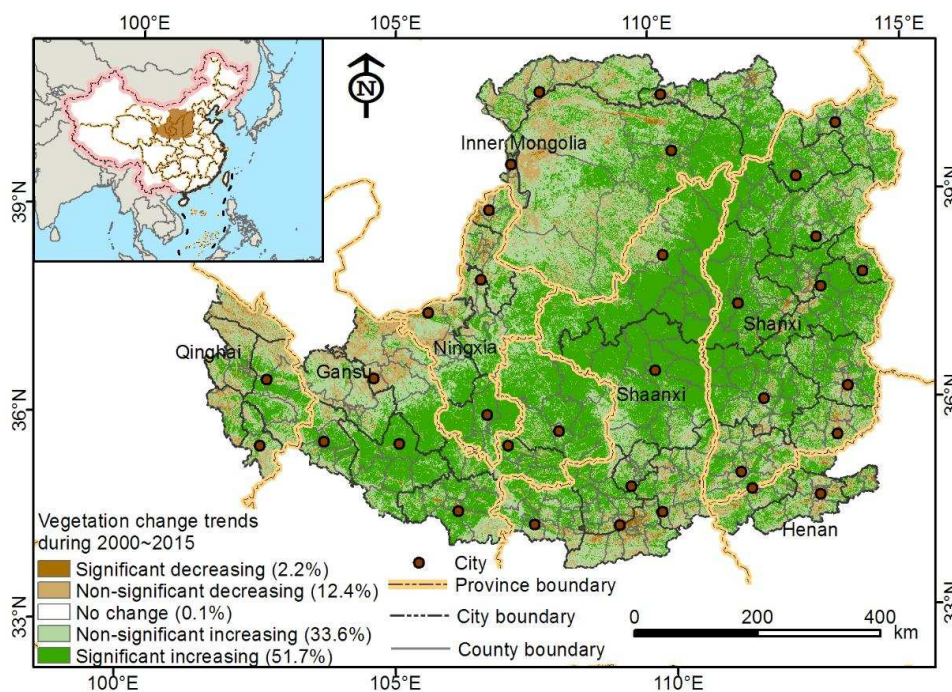
107 **2. Materials and methods**

108 *2.1. Study area*

109 The Loess Plateau is located in the north of China (33°43′–41°16′N,
110 100°54′–114°33′E) and covers an area of approximately 640,000 km². It is distributed
111 across 7 provinces and 44 municipalities consisting of 334 county level administrative
112 units. The Loess Plateau is characterized by inland arid and semi-arid climatic
113 conditions with concentrated precipitation, intensive evaporation, a water-limited
114 landscape and a fragile ecological environment.

115 Historically, intensive farming practices concentrated on sloping land led to the
116 loss of natural forest and grassland, resulting in severe water shortages and
117 accelerated soil erosion in this region. Since the beginning of this century, ecological

118 restoration projects like the GTGP and Natural Forest Protection Projects have been
 119 implemented nationwide in China, and almost all of the counties in the Loess Plateau
 120 are involved in these with the result that the landscape pattern has experienced
 121 remarkable changes. Several empirical studies have revealed evidence of significant
 122 vegetation greening trends in China (Fu et al., 2017; Lü et al., 2015), especially in the
 123 Shaanxi, Shanxi, Ningxia and Gansu provincial administrative regions (Lü et al.,
 124 2015). Areas with significant vegetation greening trends during 2000 to 2015 cover
 125 more than half the Loess Plateau (51.7%), while significant vegetation browning areas
 126 cover only 2.2% of the region (Fig. 1). Such changes may have impacts on the
 127 delivery of multiple ESs, and is the focus of current research.



129 **Fig. 1.** Location of the Loess Plateau in China. To characterize the change of
 130 vegetation in the Loess Plateau, we used data of fractional vegetation cover to
 131 represent vegetation greening or browning trends using the methods reported by Lü et
 132 al. (2015).

133 *2.2. Quantifying of ecosystem services*

134 Ten ESs were selected based on their regional importance and data availability
 135 and were mapped across the Loess Plateau (Table 1). They included 4 provisioning, 5

136 regulating, and 1 cultural service, as defined in the Common International
137 Classification of Ecosystem Services (CICES) (Haines-Young et al., 2012).
138 Considering the regional importance of vegetation restoration, the 10 selected ESs
139 capture important natural and artificial landscape characteristics of the Loess Plateau.
140 We used measurable proxies from statistical surveys combined with the InVEST
141 model (version 3.3.3) and a biophysical indicator (NPP) to construct indicators for the
142 supply of the 10 ESs, because many provisioning or cultural services cannot be
143 measured directly. Regulating services were reflected by ecosystem function changes
144 during the vegetation restoration process and were measured at 250 m spatial
145 resolution. Datasets including statistical, meteorological and remote sensing data are
146 publicly available so that our results could be transferable and comparable with other
147 locations. The land use data for 2000 and 2015 was obtained from the Institute of
148 Remote Sensing and Digital Earth, Chinese Academy of Science
149 (<http://english.radi.cas.cn/>). This was generated through interpretation of 30 m spatial
150 resolution Landsat TM (<https://earthexplorer.usgs.gov/>). The land use and land cover
151 types were classified into six categories: forest lands, grasslands, croplands, wetlands,
152 built-up lands and unused land. Other data is described in detail in the following
153 sections.

154 *2.2.1 Provisioning services*

155 Data on grain production, oil crop production and livestock supply were obtained
156 from the China Statistical Yearbook (County-level) and the provincial statistical
157 yearbook of the seven provinces (Fig. 1) in 2000 and 2015. Grain production includes
158 the yields of summer grain (i.e. wheat) and autumn grain (i.e. rice, corn and soja),
159 which provide the main regular crops in the Loess Plateau. Oil crop production (e.g.,
160 canola and peanut) was classified as human food and nutrition obtained from
161 terrestrial ecosystem according to the CICES classification (Haines-Young et al.,
162 2012). The main types of livestock in the Loess Plateau are goats, cattle and pigs.
163 Thus, we counted the total amount of beef, mutton and pork as the livestock product
164 supply.

165 Water yield was used as an indicator of water supply and was calculated by the

166 InVEST Water Yield Model. Based on the Budyko curve and annual average
167 precipitation, this calculates the annual water yield for each pixel as annual
168 precipitation minus the annual actual evapotranspiration (see the InVEST User's
169 Guide) (Sharp et al., 2016). It should be noted that in the InVEST Water Yield Model,
170 the Z parameter is an empirical constant reflecting the seasonal distribution of
171 precipitation with a range from 1 to 30. As several studies have determined ω
172 empirically (Donohue et al., 2012; Liang and Liu, 2014; Xu et al., 2013), it is
173 operationally possible to estimate Z according to the relationship between ω and Z
174 (Sharp et al., 2016). Hence, we quantified Z as 18.0 and 19.7 in 2000 and 2015,
175 respectively. Detailed information on data requirements and their sources are provided
176 in the supplementary material, Table S1.

177 2.2.2 Regulating services

178 Carbon sequestration in terrestrial ecosystems is vital to mitigate carbon
179 dioxide-driven climate warming at local and regional scales. How terrestrial
180 ecosystems are managed, for example through vegetation restoration or alternative
181 agricultural practices, can lead to changes of carbon storage and sequestration (Sharp
182 et al., 2016). In this study, we used net primary productivity (NPP) as an indicator for
183 carbon sequestration, computed using the CASA (Carnegie-Ames-Stanford)
184 ecosystem model (Van der Werf et al., 2006). NPP data products in 2000 and 2015
185 were generated with a 250 m spatial resolution from MODIS imagery.

186 Soil erosion has had severe issue that significantly impacted on the
187 environmental quality and social-economic development of the Loess Plateau.
188 Therefore, assessments of erosion control under changing land cover are important to
189 understand the efficiency of vegetation restoration (Fu et al., 2011). We first
190 quantified annual potential soil loss using the InVEST Sediment Delivery Model,
191 which is based on the revised universal soil loss equation (RUSLE). Then, actual soil
192 loss was calculated as the annual potential soil loss multiplied by a vegetation cover
193 (C) factor and an erosion control practice (P) factor, which were estimated by using
194 the vegetation cover-based method (Cai, 2000) and the slope-based method (Lufafa et
195 al., 2003), respectively. Finally, erosion control was calculated as soil loss for bare

196 soil (i.e. the potential soil loss) minus that under the current land use and land cover
197 pattern (i.e. the actual soil loss) (Lattera et al., 2012).

198 Baseflow regulation is the discharge from underground storage, and can be the
199 main source of streamflow in the dry season (Kim and Yang, 2017). Under highly
200 seasonal climates, baseflow is likely to provide greater information value than quick
201 flow (including direct runoff, interflow, and direct precipitation), and thereby
202 understanding baseflow regulation is crucial for the assessment of low-flow
203 characteristics in landscape management (Kim and Yang, 2017). We used the InVEST
204 Seasonal Water Yield Model to quantify the relative contribution of landscape factors
205 to the generation of baseflow. In this model, maps of monthly precipitation and
206 reference evapotranspiration were both provided as raster-based maps. A raster map of
207 the 7 climate zones in the Loess Plateau and the number of rain events for each zone
208 were also provided to represent the variability of rainfall events over such a large area.
209 Detailed information on other data requirements and sources are given in the
210 supplementary material, Table S1.

211 Nutrient retention by natural ecosystems is of particular interest for surface water
212 quality particularly for avoiding eutrophication, cleaning drinking water and saving
213 treatment costs. Nonpoint-source nitrogen (N) and phosphorus (P) from agricultural
214 or urban landscapes provide major threats to surface water quality (Keeler et al., 2012;
215 Qiu and Turner, 2013). Here, we applied the InVEST Nutrient Delivery Model to
216 generate spatial information about the mitigating contribution of the ecosystem to N
217 and P exports. The model estimates the amount of N or P that are exported from
218 upslope pixels and that eventually reach downslope flows, with the land use types
219 playing a key role in determining nutrient loading and filtration efficiency. The land
220 use-based nutrient loading rates and export coefficients were determined from
221 empirical data (Table S1). The results of nutrient exports are negative indicators: the
222 higher the N and P export, the lower the nutrient retention capacity.

223 *2.2.3 Cultural service*

224 Forest recreation was selected to represent a cultural services in the Loess
225 Plateau due its importance in the process of vegetation restoration. Following

226 previous research methods (Raudsepp-Hearne et al., 2010; Yang et al., 2015), we
227 quantified this indicator from the percent of forest cover (i.e. areas of all forest
228 divided by the total area of the county), as calculated from the land cover maps of
229 2000 and 2015.

Ecosystem service	Indicators	Description	Methodology	Data source	Analysis scale
Provisioning	Grain production (GRAIN)	Yield of rice, wheat, corn and soja, t/hm ²	Measurable proxies	Statistical Yearbook	County
	Oil crop production (OIL)	Oil yield, t/hm ²	Measurable proxies	Statistical Yearbook	
	Livestock supply (LIVESTOCK)	The amount of beef, mutton and pork, t/hm ²	Measurable proxies	Statistical Yearbook	
	Water supply (WAT_SUPP)	Annual water yield, m ³ /hm ²	InVEST model	Table S1 in Appendix	250m pixel
Regulating	Carbon sequestration (CARBON)	The above ground biomass, gC/ hm ²	Biophysical indicators by NPP	CASA model	
	Erosion control (ERO_CON)	Sediment retention with reference to bare area, t/hm ²	InVEST model	Table S1 in Appendix	
	Baseflow regulation (BASEFLOW)	The capacity of slow release flow	InVEST model	Table S1 in Appendix	250m pixel
	N retention (N_RETEN)	total nitrogen export reaches the stream, t/hm ²	InVEST model	Table S1 in Appendix	
	P retention (P_RETEN)	total phosphorus export reaches the stream, t/hm ²	InVEST model	Table S1 in Appendix	
Cultural	Forest recreation (FOR_REC)	Percent of land that is forested	Measurable proxies	The percent of forest cover	County

232 *2.3. Spatial scale and data summaries*

233 Each ES was mapped in ArcGIS to visualize and compare their spatial patterns in
234 2000 and 2015. The ten ESs were assessed at the county scale. This is the smallest
235 unit over which socio-economic and agricultural census information are reported, and
236 also the smallest unit of integrative governance and decision-making on ESs in China.
237 For the ecosystem services that were calculated over a 250 m grid, the mean value for
238 each county was taken using a standard zonal raster analysis.

239 The county level ESs were normalized by area to account for the wide variety of
240 county sizes. To facilitate the cluster analysis, ES values were standardized using
241 min-max normalization (Derksen et al., 2015). The values of nutrient exports (i.e. N
242 exports and P exports) were transformed (inverted) to a nutrient retention capacity
243 measure such that higher values of N or P retention corresponded to higher ES values
244 in order to enable comparisons among ESs (Raudsepp-Hearne et al., 2010). The
245 spatial clustering of each ES was determined using a global Moran's I spatial
246 autocorrelation measure as implemented in ArcGIS.

247 *2.4. Interactions among ESs and delineation of ES bundles*

248 Pearson parametric correlation tests (R v3.5 statistical software) were undertaken
249 to assess the pairwise relations between ecosystem services. A cluster analysis was
250 used to identify groups of counties whose ES bundle types had similar compositions
251 of ES values, ES tradeoffs and synergies among ESs (Raudsepp-Hearne et al., 2010;
252 Spake et al., 2017). A *k-means* cluster analysis (SPSS v20) was applied and the results
253 were mapped in ArcGIS to visualize the spatial pattern of ES bundles. Rose plots of
254 mean ESs for each cluster were constructed to visualize the properties of each cluster
255 using the *ggplot2* R package (Wickham, 2016).

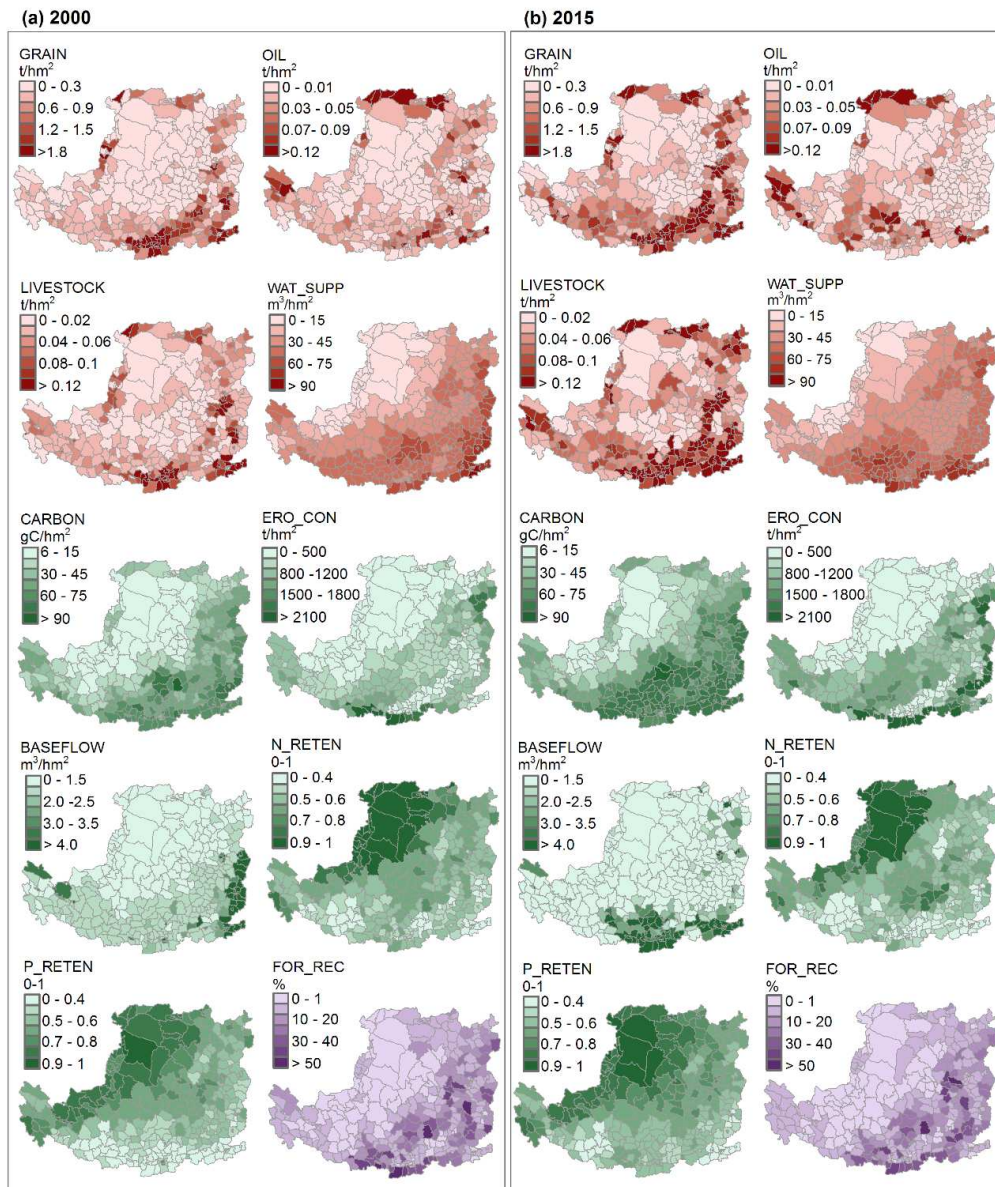
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257 **3. Results**

258 *3.1. Spatial patterns and changes of ESs*

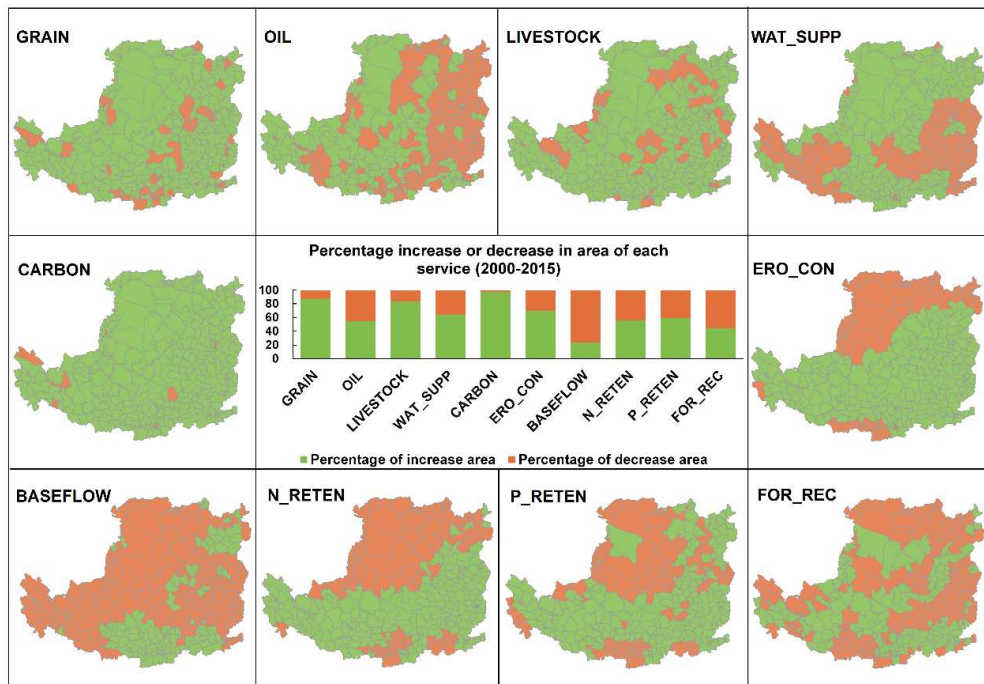
259 Each ecosystem service exhibited significant positive spatial autocorrelation,
260 indicating spatially clustering rather than a random distribution ($P < 0.01$; Fig. 2).
261 Moran's I-values for all the 10 ESs are provided in the supplementary material, Table
262 S2. The three provisioning services (grain, oil and livestock) in 2000 and 2015 were
263 found to be spatially autocorrelated around peri-urban areas, which may be related to
264 the food demands and population density of urban areas. The distributions of water
265 supply and all of the regulating services were found to relate more to the natural
266 environment particularly precipitation, proximity to rivers and specific ecosystems.
267 For example, the spatial distribution of water supply decreased from southeast to
268 northwest both in 2000 and 2015, which was closely linked to the regional
269 precipitation gradient. Forest recreation had a higher concentration in the tourist
270 attractions like national parks.

271 We calculated the percentage of increase or decrease area of each service at the
272 regional scale to quantify the spatial changes of each ES (Fig. 3). All of the ESs,
273 except baseflow regulation and forest recreation, were found to improve between
274 2000 and 2015, especially grain production and carbon sequestration. Specifically,
275 grain and livestock production provisioning services were found to improve in most
276 counties. In contrast, decreases in the areas of oil crops production and water supply
277 were observed in Shanxi and Gansu provinces. Overall, water supply increased
278 slightly (Fig. 3) as was found in a quantitative evaluation of hydrological regulation in
279 the Loess Plateau from 2000 to 2012 (Jiang et al., 2016b). Carbon sequestration
280 improved in approximately 97% of the Loess Plateau. In areas of erosion control, N
281 and P retention increased and the spatial patterns of this expansion were consistent
282 with vegetation coverage increases (Fig. 1), implying a positive influence of
283 vegetation restoration on erosion control and nutrient retention. However, baseflow
284 regulation decreased dramatically in most counties, and a decrease in forest recreation
285 was observed in many counties in the northeast of the Loess Plateau.



286

287 **Fig. 2.** Distributions of 10 ecosystem services across the Loess Plateau in (a) 2000
 288 and (b) 2015. The values for N and P exports were transformed into ecosystem
 289 services for nutrient retention after the standardization and normalization phase,
 290 resulting in values describing the capacity for N or P retention (ranging from 0 to 1).



291

292 **Fig. 3.** The increases and decreases in the area of each services at the regional scale.

293 The percentage increase in area indicates higher service values in 2015 than in 2000

294 and percentage decrease in area indicates lower services values in 2015 than in 2000.

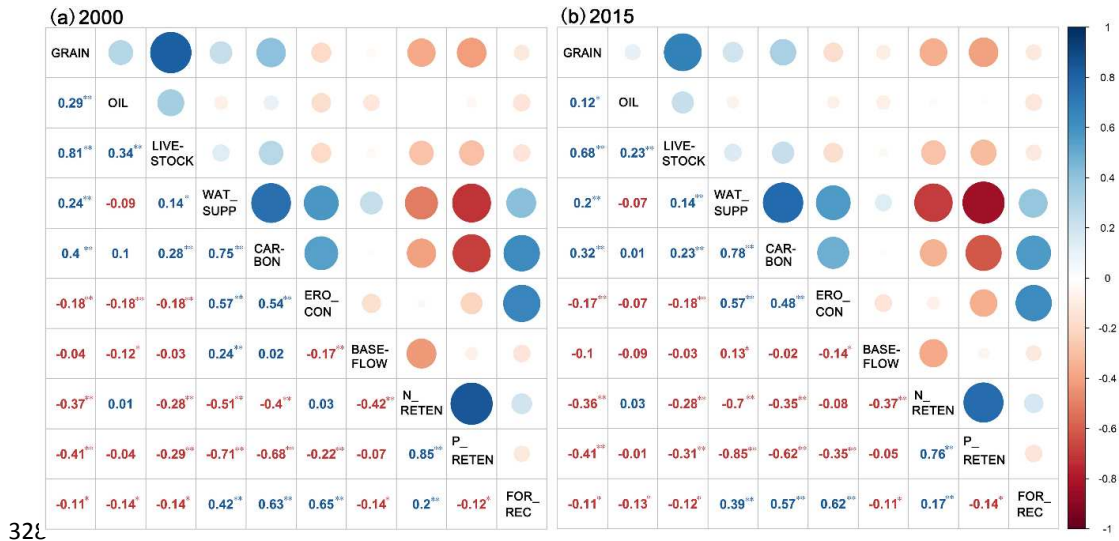
295 3.2. *Trade-offs and synergies among ESs*

296 In 2000 and 2015, most of the ESs interacted with each other to differing degrees.
297 Out of 45 possible pairs of ESs, 37 and 34 were significantly correlated in 2000 and
298 2015, respectively (Fig. 4). Trade-offs between provisioning and almost all regulating
299 services has been previously demonstrated and shown to be associated with ecosystem
300 diversity at the landscape scale (Raudsepp-Hearne et al., 2010).

301 In our study, a steady tradeoff was found between agricultural provisioning services,
302 regulating services (except for carbon sequestration), and cultural service (forest
303 recreation). N or P retention was also observed to have highly significant negative
304 correlations with water supply and carbon sequestration ($r \geq 0.5$), and moderately
305 negative correlations with grain and livestock ($0.5 > r \geq 0.3$). Baseflow was negatively
306 correlated with other ESs, while, it only had a weakly positive correlation with water
307 supply ($0.3 > r \geq 0.1$).

308 We also found that the significant synergistic relationships among ESs were more
309 frequent in provisioning and regulating services. Four provisioning services were
310 positively correlated with each other, the exception being between oil crop production
311 and water supply. For regulating services, such as carbon sequestration and erosion
312 control, N and P retention, significantly positive correlations were detected. Notable
313 potential synergies between different types of services were also observed. Water
314 supply, carbon sequestration and erosion control were found to have a strong positive
315 correlations, consistent with previous research in the Loess Plateau (Jiang et al., 2018;
316 Su and Fu, 2013). Forest recreation had highly positive correlations with carbon
317 sequestration and erosion control ($r \geq 0.5$), and a moderately positive correlation with
318 water supply ($0.5 > r \geq 0.3$).

319 In 2015, however, changes in the interactions among ESs showed weakened
320 synergies compared to 2000. For example, the synergistic relationships between grain
321 and oil crops, grain and livestock, oil crops and livestock reduced from 0.29, 0.81 and
322 0.34 to 0.12, 0.68 and 0.23, respectively. Similarly, the highly positive correlations
323 between forest recreation and regulating services (i.e. carbon sequestration and
324 erosion control) also had slightly downward trends. On the other hand, tradeoffs
325 between nutrient retention and water supply were reinforced. Generally, weakened
326 interactions among ESs were observed in 2015, including some tradeoff relationships
327 but mainly concentrating on synergies.



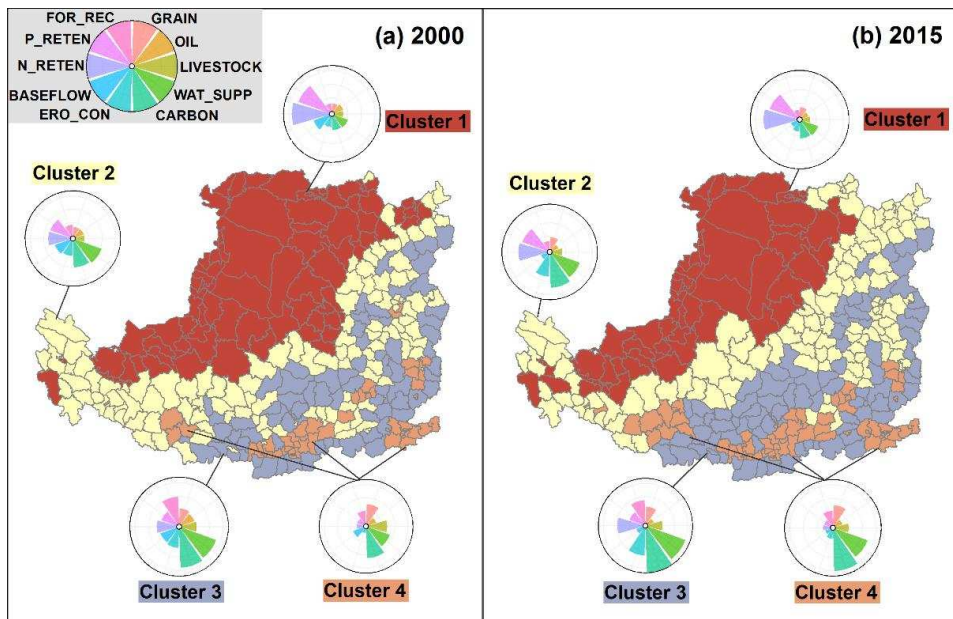
329 **Fig. 4.** Pearson correlations between pairs of ecosystem services in (a) 2000 and (b)
 330 2015 (* $P < 0.05$; ** $P < 0.01$). The lower left part of each figure indicates the Pearson's
 331 correlation coefficients (r) and the blue and red circle (upper right part) indicate
 332 positive and negative correlations, respectively.

333 3.3. Patterns and changes of ES Bundles

334 The cluster analysis grouped the 334 counties in the Loess Plateau into four
 335 distinct clusters in both in 2000 and 2015, each associated with four types of ES
 336 bundles. The ES bundles are characterized by the average values of the 10 ESs
 337 (Derkzen et al., 2015). The spatial distribution of the clusters over the counties were
 338 found to be geographically clustered (Moran's $I > 0.65$, $P < 0.01$), to have distinct
 339 spatial distributions in both 2000 and 2015 and the four types of ES bundles were
 340 characterized by significant spatial heterogeneity of ESs (Fig. 5). Cluster 1 is
 341 distributed across the north of the Loess Plateau with high values of nutrient retention
 342 capacity but the lowest values of other ESs. Cluster 2 runs through the
 343 farming-grazing transition zone and has moderate values of water supply, carbon
 344 sequestration, and nutrient retention and relatively low (but even) values of other ESs.
 345 Cluster 3 is associated with peri-urban areas and the most significant vegetation
 346 restoration areas. It has the highest values of water supply, carbon sequestration and
 347 forest recreation. Cluster 4 is found in the main urbanized areas and has the lowest
 348 nutrient retention and baseflow regulation.

349 Comparison of ES bundles between 2000 and 2015 reinforced the observed
 350 spatial heterogeneity of the ten ESs. Gaps between agricultural provisioning services
 351 and baseflow regulation with other ESs were more obvious in 2015, although most of
 352 the ESs were generally improved. For example, for Cluster 2 and Cluster 3, the high

353 values of water supply and carbon sequestration were strengthened but affected the
 354 balance of other ESs compared to 2000 as a consequence. Spatially, the number of
 355 counties involved in Cluster 1 and Cluster 2 decreased from 88 and 121 to 67 and 116,
 356 respectively, while Cluster 3 and Cluster 4 increased from 71 and 54 to 82 and 69,
 357 respectively. The counties in Cluster 1 and Cluster 2 had a northward shift, which
 358 were accompanied by transverse expansion in Cluster 3 and Cluster 4 (Fig. 5).



359
 360 **Fig. 5.** Ecosystem services bundles in (a) 2000 and (b) 2015. The rose plots represent
 361 the average values of ecosystem services detected within each of the clusters. The
 362 maps show the spatial distribution of the counties characterized by each ecosystem
 363 services bundle.

364 **4. Discussions**

365 *4.1. The clustered distributions of ESs*

366 Knowledge of the spatial characteristics and changes of ESs could lead to more
367 informed ecosystem management and landscape planning. The spatially clumped
368 distributions, which could be the widespread characteristics for most ESs, has been
369 found in several studies involved grids, neighbourhoods, and municipalities scales
370 with different size of analysis units (Derkzen et al., 2015; Raudsepp-Hearne et al.,
371 2010; Turner et al., 2014). But some services like tourism and livestock that are
372 subject to intense anthropogenic disturbance have been found to be more randomly
373 distributed than spatially clustered especially in semi-natural or artificial systems
374 (Yang et al., 2015). In a similar way, in this study oil crop production, livestock
375 production and forest recreation, although found to be significantly clustered, with
376 positive Moran's I values, were the least clustered and exhibited individual landscape
377 distribution patterns (Table S2). This indicates that these services could be easily
378 affected by anthropogenic processes such as urbanization and suggests the need for
379 ES supply and demand modelling to support any proposed change in their distribution,
380 for example to optimize the efficient natural resources use (Gulickx et al., 2013). Thus,
381 in the peri-urban areas, conservation of dispersed small sites delivering these services
382 (i.e. oil crops, livestock and forest recreation) may provide an important way of
383 guaranteeing agricultural production supply and avoiding increases in transportation
384 and transaction costs.

385 *4.2. Vegetation restoration is critical for ESs*

386 Environmental programmes supporting sustainable land management and
387 ecosystem restoration seek to preserve biodiversity, improve the multiple ESs supply
388 and enhance regional livelihoods. Some of these have achieved remarkably positive
389 impacts. In South Africa, the combination of light grazing and nature restoration has
390 been found to facilitate ESs supply of provisioning, regulating, and culture services
391 (Petz et al., 2014). A comprehensive assessment of the Tibet Plateau also confirmed
392 that conservation projects positively impacted on the improvement of ESs such as
393 water retention, sand fixation, and carbon sequestration (Huang et al., 2018), further
394 supporting the role of restoration programmes as a major cause of improvements to
395 regional supplies of multiple ESs.

396 Sustainability strategies, such as agricultural land consolidation and small
397 watershed improvement guarantees the continued growth of agricultural production,

398 even under large-scale restoration and afforestation (Bryan et al., 2018). In our study,
399 the main types of agricultural services in the Loess Plateau, namely grain, oil crops
400 and livestock increased in area (Fig. 3). For most counties, negative impacts of
401 large-scale vegetation restoration on agricultural production have been minimized
402 because restoration activities were mainly focused on steep and low-productivity land
403 (Lu et al., 2013). Moreover, numerous check dams distributed in the Loess Plateau
404 offer an advantage of producing large and flat areas for crop production behind the
405 dams, which have a much higher productivity for sustaining food security (Fu et al.,
406 2017; Wang et al., 2011). Technological advances related to cultivars as well as the
407 mitigation of soil salinization in arid and semi-arid regions have also boosted
408 productivity (Bryan et al., 2018; Zhang, 2011). But notable exceptions can be
409 observed in east of the Loess Plateau for oil crops production as a consequence of
410 urbanization (Fig. S1). For regulating services, empirical research has indicated no
411 significant change in precipitation or temperature across the entire Loess Plateau over
412 the last decade, suggesting that the ecological restoration programmes that were
413 implemented to be the dominant cause of the observed significant increases in carbon
414 sequestration (Feng et al., 2013). Furthermore, vegetation restoration in the Loess
415 Plateau has reduced soil erosion to historically low levels and contributed greatly to
416 water quality improvements and river sediment controls (Chen et al., 2015; Jiang et al.,
417 2018). As part of this restoration process, engineering measures for soil-erosion
418 control such as check dams, terracing and reservoirs altered the microtopography of
419 the land surface, which played an important role in intercepting precipitation and
420 reducing sediment generation (Fu et al., 2017). Wang et al. (2015) confirmed that
421 these engineering measures were the major reason for reductions in sediment load
422 from the 1970s to 1990s, while vegetation restoration has been the major contributor
423 to reductions in soil erosion since 2000. This is because the capability of existing
424 dams and reservoirs to trap sediments is declining (Wang et al., 2015). Therefore, in
425 our research period (i.e. 2000 to 2015) the observed improvements in erosion control
426 and nutrient retention can be mainly attributed to large-scale vegetation restoration in
427 the Loess Plateau. The enhanced carbon sequestration, erosion control and nutrient
428 retention observed in 2015 (Fig. 3) are all supported by the above cited research.

429 The influences of large-scale newly planted vegetation on water resource is more
430 complicated, especially in seasonally dry areas such as the Loess Plateau.
431 Precipitation is the major source of water to ecosystems in the Loess Plateau (Feng et
432 al., 2016; Feng et al., 2013), and was not found to increase or decrease significantly

433 during the period 2000 to 2015. Therefore, the decreases in water supply and baseflow
434 were mainly driven by the increases of vegetation cover in the Loess Plateau. This
435 allowed more evaporation as more precipitation is intercepted by vegetation canopy
436 (Yang et al., 2012), while vegetation transpiration effects also consumed precipitation
437 input. Therefore, re-vegetation increased evapotranspiration but decreased runoff
438 (Feng et al., 2016). In arid and semi-arid watersheds, baseflow is more sensitive to the
439 changing evapotranspiration caused by vegetation-associated shifts (Tang et al., 2016).
440 For the Loess Plateau with thick loess deposits, only a small proportion of infiltrated
441 rainfall is able to recharge groundwater, even though the increased litter layers can
442 favor precipitation infiltration (Zhang et al., 2008). By contrast, re-vegetation caused
443 excessive use of the limited soil water available through plant root uptake, which
444 slowed the infiltration process and offset the potential gains in groundwater recharge
445 (Liang et al., 2015; Ribolzi et al., 2018). Thus, in this study baseflow became more
446 unsteady and showed a large decrease (Fig. 3). Consequently, we recommended that
447 baseflow regulation should be included as a key indicator for a comprehensive
448 understanding of changes in ESs under vegetation restoration programmes.

449 *4.3. The tendency of depressed synergies between ESs*

450 ESs are not independent of each other and their relationships may be non-linear,
451 therefore understanding their interaction requires broad studies that consider several
452 ESs in the same system (Howe et al., 2014). The formation of tradeoffs and synergies
453 among ESs can be attributed to land use conflict or consistency, common drivers, or
454 interactions among ESs (Xu et al., 2017). For example, tradeoffs between
455 provisioning and other ESs often reflect the conflicts between agricultural land use
456 and uses supporting other services (Foley et al., 2005). Sometimes tradeoffs are the
457 result of direct interactions between ESs (Raudsepp-Hearne et al., 2010) such as the
458 highly negative correlations between water supply and the two types of nutrient
459 retention found in our study. The negative relationship between baseflow and erosion
460 control suggests a tradeoff of ecohydrological effect between ESs (Fig. 4) caused
461 mainly by topographic and hydrometeorological factors. In steeper sloping areas,
462 most of the rainfall runs as overland flow with a small time lag and short-lived peak
463 flows, so that the groundwater recharge will be less effective, leading to the smaller
464 baseflow (Costa and Bacellar, 2007; Lee et al., 2014). The findings of our study, in
465 line with the above research, show high levels of erosion control distributed over the
466 loess hilly areas and lower baseflow regulation (Fig. 2).

467 On the other hand, the high positive correlations between grain production and

468 livestock supply, a well-known synergy in the provisioning services, has been
469 confirmed in studies in Canada, Denmark as well urban-rural complexes in China
470 (Raudsepp-Hearne et al., 2010; Turner et al., 2014; Yang et al., 2015). In our study,
471 the three agricultural provisioning services were all positively correlated with each
472 other in the Loess Plateau (Fig. 4). We also found synergies between the three
473 agricultural provisioning services and carbon sequestration, which was different from
474 researches that reflect the competition of land use between agricultural production and
475 forest land cover (Yang et al., 2015). This could be a further evidence that the adverse
476 effects of vegetation restoration on agricultural production has been mitigated by
477 technological advances and policy support. Finally, cultural services exhibited
478 positive relationships to most regulating services, suggesting non-antagonistic
479 relationships with land availability (Turner et al., 2014).

480 In the comparison between 2000 and 2015, however, we noted that these
481 synergies were generally weakened despite improvements in most ESs. Land use and
482 land cover change is the most important factor influencing changes in ESs and
483 modifying ES trade-offs and synergies (Li and Wang, 2018). Human disturbance of
484 land cover can diminish the underlying functional interdependencies among ESs
485 (Crouzat et al., 2015; Xu et al., 2017). In this study, the increases in forest, grassland
486 and built-up areas were the major contributors to land use change (Fig. S1).
487 Fragmented farmland areas in peri-urban areas decreased because of vegetation
488 restoration and urbanization processes, resulting in reduced spatial homogeneity and
489 weakened synergies among agricultural ESs (Fig. 4). A similar trend was observed in
490 the positive relationships between forest recreation and other services (Fig. 4), in
491 which forest recreation decreased in 2015 (Fig. 3). Therefore, the moderating impact
492 of conservation on land use change on ESs synergies may be another benefit of
493 conservation on the small, dispersed sites in peri-urban areas.

494 In addition, synergies between water supply and carbon or soil-associated
495 services have also been reported in other research (Jiang et al., 2018; Yang et al.,
496 2015), which were also observed in the Loess Plateau (Fig. 4). Nevertheless, further
497 analysis on the correlations of the three ESs in different periods revealed that it was
498 more likely to be pseudo-positive (Jiang et al., 2016a; Su and Fu, 2013). Because, it is
499 self-evident that the increased carbon sequestration could retain more sediment but
500 less freely water flows and thereby produce lower water yield. These evidences
501 demonstrated that interactions of ESs become more uncertain and difficult to manage
502 as the temporal or spatial scales increase (Howe et al., 2014). Incorporating historical

503 data and considering the changes in correlations between multiple ESs to quantify
504 temporal changes in addition to changes in spatial relationships could offer an
505 opportunity to address these issues.

506 *4.4. The role of ES bundles in regional-scale management*

507 ES bundles can be derived by grouping similar combinations of ESs across a
508 landscape. They can help to delineate linked ESs and facilitate consideration of the
509 multiple tradeoffs or synergies in land management decision making (Kareiva et al.,
510 2007; Raudsepp-Hearne et al., 2010). Early studies focused on the spatial distributions
511 and features of bundle types, such as agriculture, forestry, and various mixed bundles,
512 and the degree to which patterns of ES organization could be identified in human
513 dominated landscapes (Queiroz et al., 2015; Turner et al., 2014). The ES bundle
514 patterns in the Loess Plateau showed some similarities with patterns found in other
515 studies. For example, high levels of cultural service in Denmark were mostly found
516 around larger cities as peri-urban landscapes provide important areas for cultural
517 services (Turner et al., 2014). Cluster 3 in our study grouped counties in peri-urban
518 areas and was found to have the highest value of forest recreation. Moreover,
519 grouping similar ESs bundles into analysis units implies that they require common
520 environmental issues and challenges to be considered as management considerations
521 (Yang et al., 2015). The four clusters in our study were visually linked to aggregated
522 geographical endowments of the Loess Plateau, such as extreme water-limited
523 landscape in Cluster 1 and lower values of regulating services due to large area of
524 impervious surface in Cluster 4.

525 The differences between the findings of this study with others research relates to
526 changes in bundling ES patterns associated with a large-scale vegetation restoration
527 programmes. These resulted in a dramatic increases in carbon sequestration and
528 decreases in baseflow regulation in 2015 (Fig. 5) as a consequence of afforestation
529 impacts on streamflow in the dry season. This finding has been verified by field
530 studies that have shown that afforestation decreases stream flow and lowers local
531 groundwater tables in drylands (An et al., 2017; Lu et al., 2018). Bundles of ESs in a
532 Swedish landscape also demonstrated that trade-offs appear among services whenever
533 a particular type of service is maximized (Queiroz et al., 2015). Similarly, in this study,
534 the balance of some bundles in 2000 was destabilized in 2015, such as Cluster 2 and
535 Cluster 3 (Fig. 5). The bundle changes indirectly indicated the tendency of weakened
536 synergies among agricultural ESs (Fig. 4), as the reduction in oil crops production
537 from Cluster 1 to Cluster 4 shows (Fig. 5b).

538 Unanticipated and unintended trade-offs can occur when management focuses on
539 only one ES at a time (Bennett et al., 2009). However, there is no generalizable set of
540 rubrics to ensure win-win solutions, thus acquiring knowledge and understanding of
541 how the trade-offs occur locally is more likely to achieve win-win situations (Howe et
542 al., 2014). In this respect, consideration of bundles captures information about how
543 the interaction of ESs changes over time, which along with visualizing ES
544 compositions, can facilitate and inform landscape-scale ecosystem management. Any
545 comprehensive understanding of the drivers of ES bundles needs to capture associated
546 social-ecological variations, which involves using a wide range of information on
547 population pressure, social economics and land use, with fine resolution over regional
548 geographical extents (Meacham et al., 2016). This is beyond the scope of this study
549 but could be a priority for further investigation.

550 **5. Conclusions**

551 Using the analytical framework of ES bundles, we explored changes in the
552 spatial distribution, bundle composition and interactions of ten crucial ESs across the
553 Loess Plateau of China over a period of rapid policy-led vegetation restoration.
554 Benefited from the policy supports and highly sensitive vegetation restoration, the
555 clumped ESs generally improved from 2000 to 2015, especially in agricultural
556 production and carbon sequestration. Whereas, the synergies between ESs were
557 weakened to some extent due to the reduction of farmland landscape in peri-urban
558 areas. More importantly, identifying changes in bundle patterns of the ten services
559 explicitly indicated the that increases in carbon sequestration and decreased in
560 baseflow regulation were driving some trade-offs among ESs. Our analysis suggested
561 that vegetation restoration programmes are a major contribution to the improvement
562 of ESs supply but focusing on particular types of services could lead to greater ES
563 heterogeneity. For fragile ecological areas like the Loess Plateau dominated by
564 drylands, baseflow regulation should be included within restoration interventions to
565 facilitate a comprehensive understanding of ES changes and their impacts.
566 Comparisons with historical data provide a perspective on the changes in correlations
567 among multiple ESs and can reveal potentially weakened functional
568 interdependencies among them. This research emphasizes the important role of ES
569 bundles in capturing the spatial distribution of changes in ES interactions at large
570 regional scales over time. Incorporating knowledge of their driving factors is a key
571 area of further study for consideration of regional social-ecological system dynamics.

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579 **Appendix A. Supplementary materials**

580 Supplementary materials to this article can be found online.

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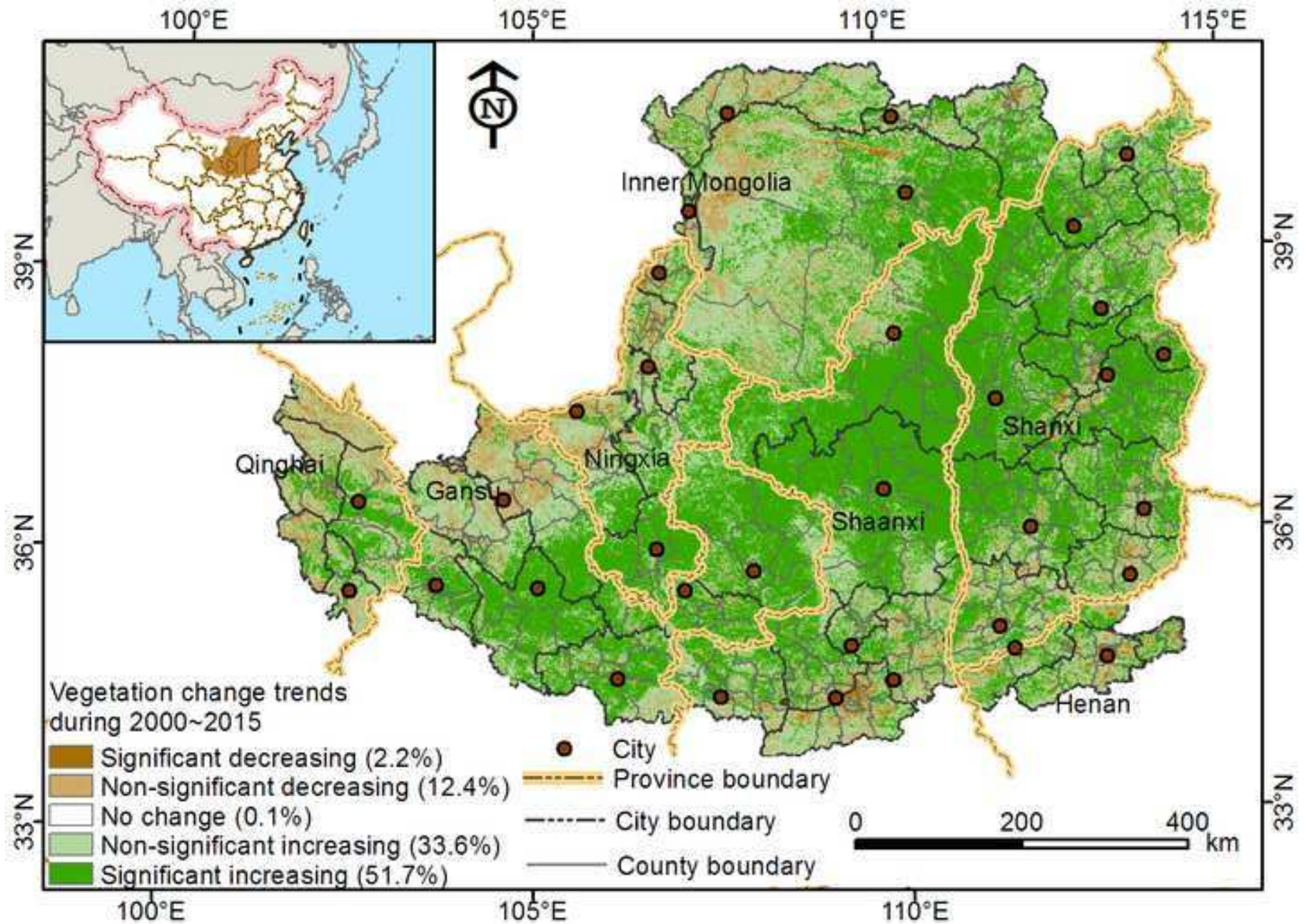


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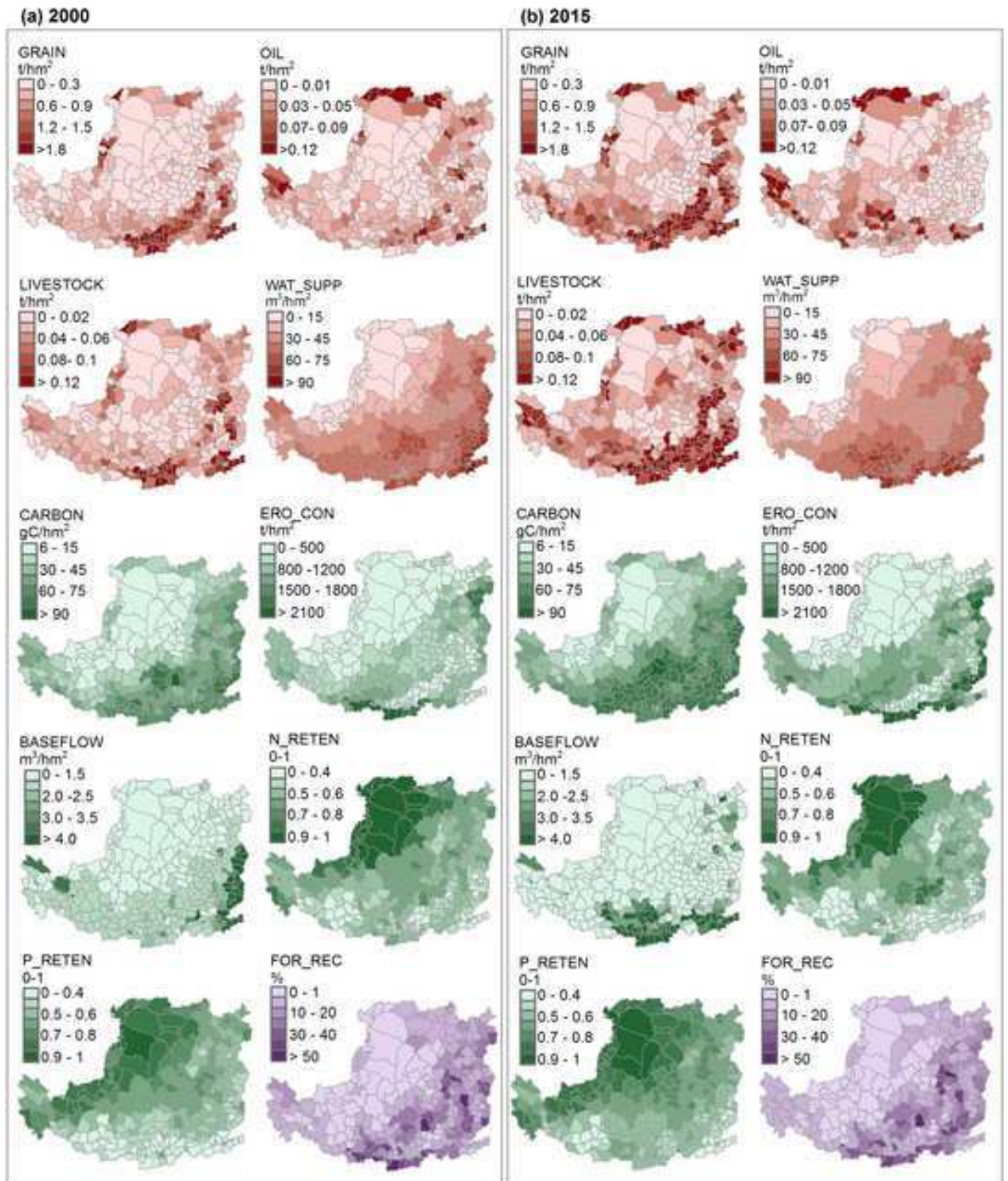


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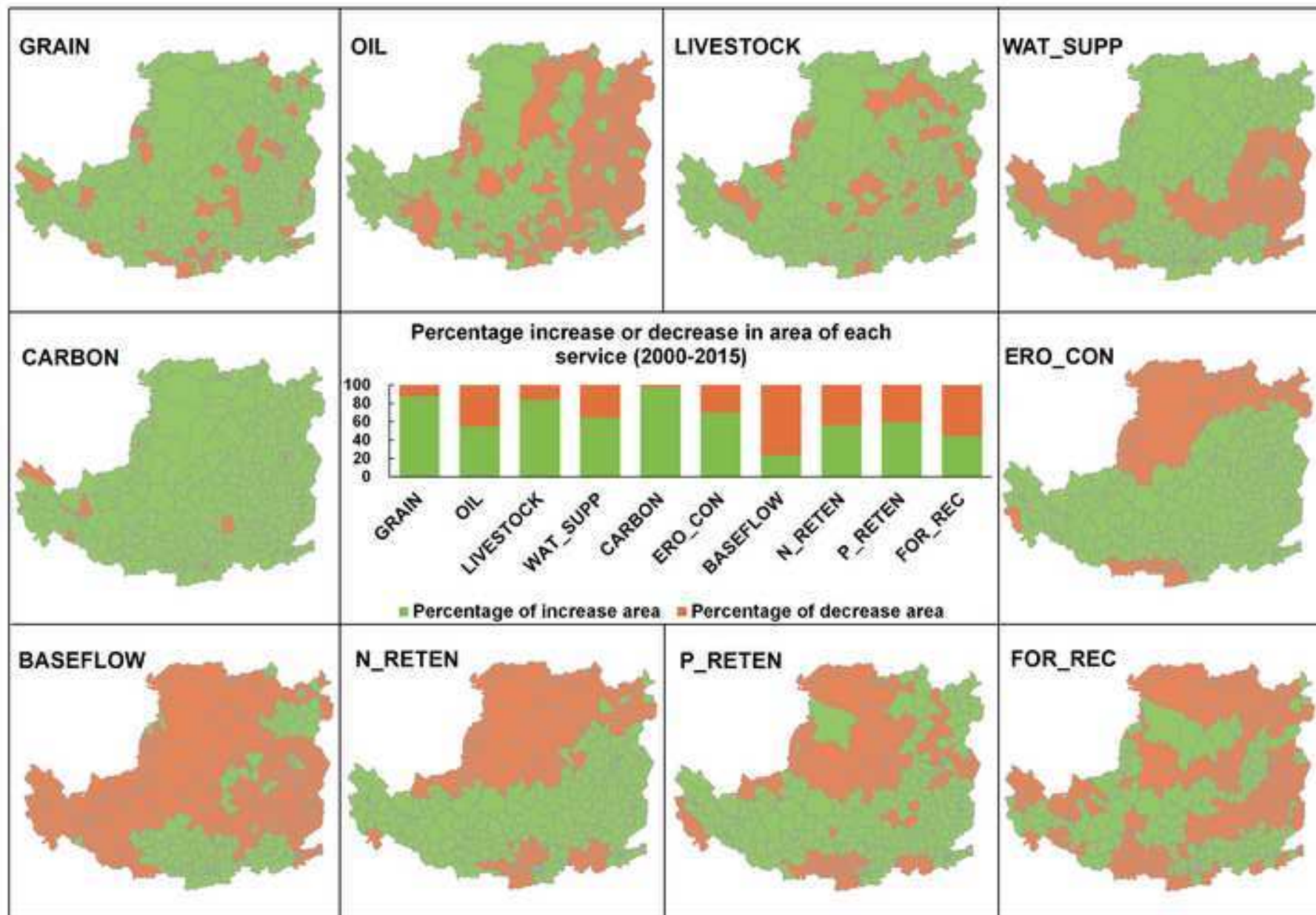
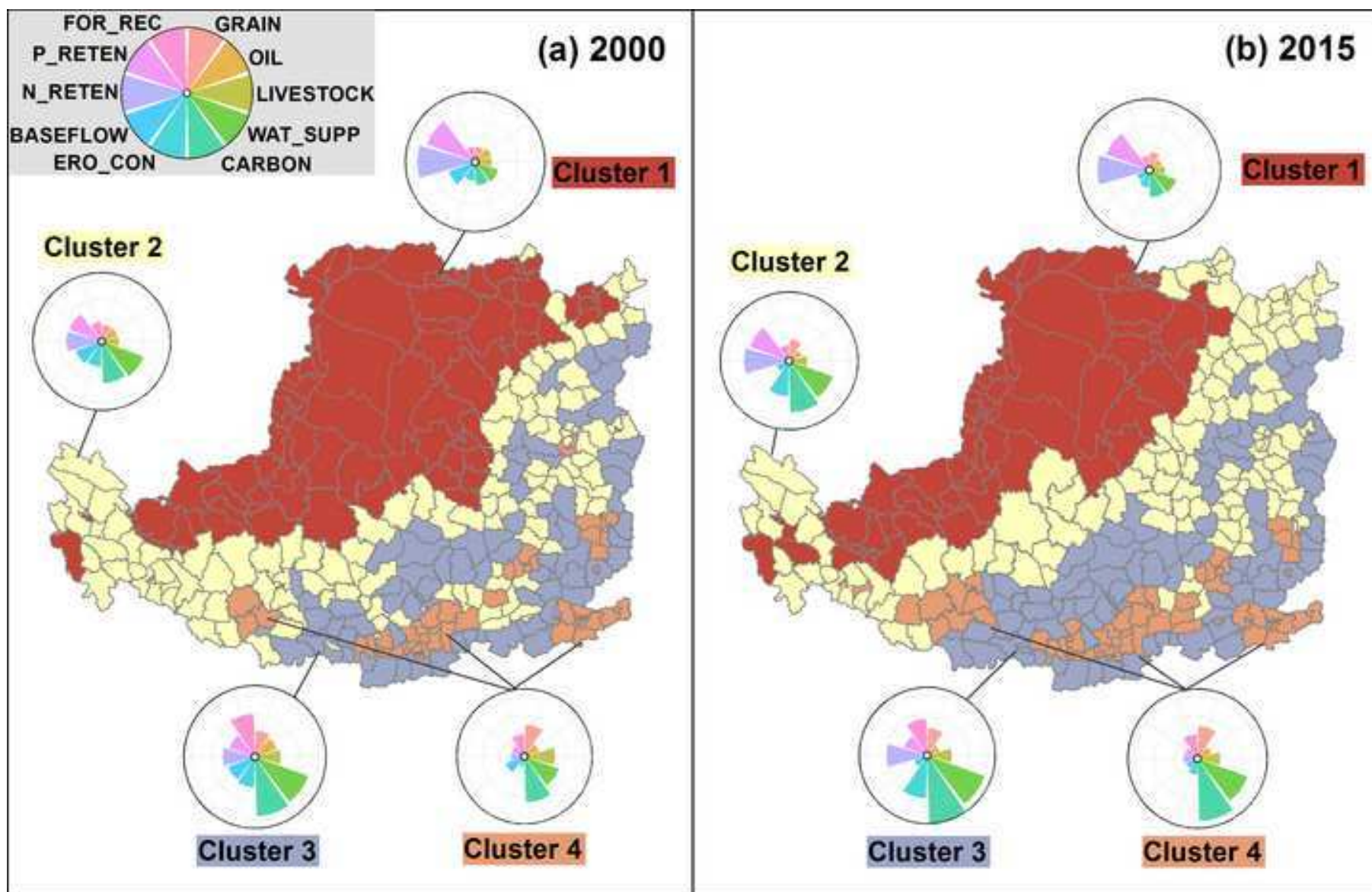


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