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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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Abstract

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

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

1. Introduction

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

One such framework is the concept of ES bundles (Raudsepp-Hearne et al., 2010). These describe temporally or spatially consistent associations, tradeoffs and synergies among sets of services and can be used to delineate areas supplying similar ES magnitudes and combinations within a landscape (Raudsepp-Hearne et al., 2010). This allows related ESs to be treated together as related entities and to be represented geographically (Turner et al., 2014). Initial work by Raudsepp-Hearne et al. (2010) demonstrated that ES bundles could allow critical trade-offs and synergies to be predicted. Later work over various spatial scales used the bundles framework to examine their interactions (Crouzat et al., 2015; Derkzen et al., 2015; Kong et al., 2018; Turner et al., 2014). These focused on delineating the ES bundle distribution to facilitate understanding of ES associations and their underlying social-ecological drivers, and for communicating the potential impacts of management decisions to policy-makers (Spake et al., 2017).

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

Benefits arising from land management interventions and natural ecosystem protection, including increased agricultural outputs and enhanced ecological conditions have been detected at the national level in China, (Bryan et al., 2018). The Loess Plateau in China has experienced significant vegetation restoration since the implementation of Grain to Green Programme (GTGP: a national programme of revegetating sloping cropland). This has had impacts on ecosystem structure and function, as well as on the supply and delivery of ESs. Recent studies in the Loess Plateau have mainly focused on the responses of vegetation, soil or water-related ESs. Feng et al. (2013) evaluated the changes in carbon sequestration and found that the ecosystems in the Loess Plateau had shifted from a net carbon source in 2000 to a net carbon sink in 2008 owing largely to the impact by the GTGP. The soil erosion control service of regional ecosystems was also significantly improved during the same period (Fu et al., 2011). Some research has also suggested a reduction of runoff during this period (Li et al., 2016; Liang et al., 2015). Moreover, the interactions among different ESs were explored to provide practical criteria for land use policy-making. Tradeoffs and synergies were often found between water yield and soil retention/carbon sequestration, and between soil retention and carbon sequestration, respectively (Su and Fu, 2013). The constraining effects of rainfall have also been detected along with tradeoffs or synergies among carbon sequestration, soil retention, and hydrological regulation (Jiang et al., 2018).

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

2. Materials and methods

2.1. Study area

The Loess Plateau is located in the north of China (33°43'–41°16'N, 100°54'–114°33'E) and covers an area of approximately 640,000 km^2. It is distributed across 7 provinces and 44 municipalities consisting of 334 county level administrative units. The Loess Plateau is characterized by inland arid and semi-arid climatic conditions with concentrated precipitation, intensive evaporation, a water-limited landscape and a fragile ecological environment.

Historically, intensive farming practices concentrated on sloping land led to the loss of natural forest and grassland, resulting in severe water shortages and accelerated soil erosion in this region. Since the beginning of this century, ecological restoration projects like the GTGP and Natural Forest Protection Projects have been implemented nationwide in China, and almost all of the counties in the Loess Plateau are involved in these with the result that the landscape pattern has experienced remarkable changes. Several empirical studies have revealed evidence of significant vegetation greening trends in China (Fu et al., 2017; Lü et al., 2015), especially in the Shaanxi, Shanxi, Ningxia and Gansu provincial administrative regions (Lü et al., 2015). Areas with significant vegetation greening trends during 2000 to 2015 cover more than half the Loess Plateau (51.7%), while significant vegetation browning areas cover only 2.2% of the region (Fig. 1). Such changes may have impacts on the delivery of multiple ESs, and is the focus of current research.

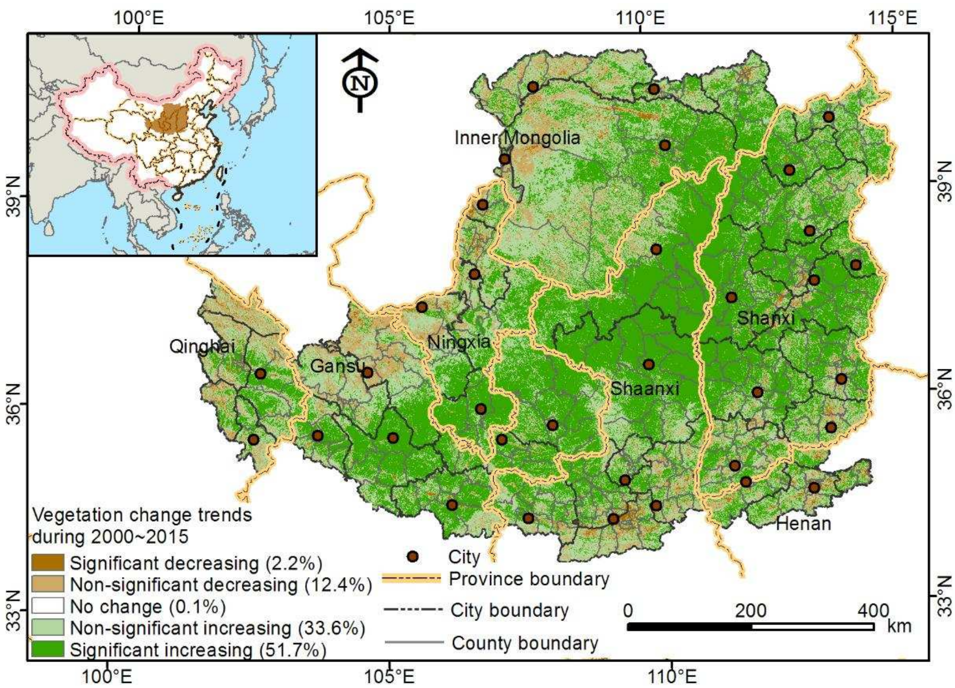

Fig. 1. Location of the Loess Plateau in China. To characterize the change of vegetation in the Loess Plateau, we used data of fractional vegetation cover to represent vegetation greening or browning trends using the methods reported by Lü et al. (2015).

2.2. Quantifying of ecosystem services

Ten ESs were selected based on their regional importance and data availability and were mapped across the Loess Plateau (Table 1). They included 4 provisioning, 5 regulating, and 1 cultural service, as defined in the Common International Classification of Ecosystem Services (CICES) (Haines-Young et al., 2012). Considering the regional importance of vegetation restoration, the 10 selected ESs capture important natural and artificial landscape characteristics of the Loess Plateau. We used measurable proxies from statistical surveys combined with the InVEST model (version 3.3.3) and a biophysical indicator (NPP) to construct indicators for the supply of the 10 ESs, because many provisioning or cultural services cannot be measured directly. Regulating services were reflected by ecosystem function changes during the vegetation restoration process and were measured at 250 m spatial resolution. Datasets including statistical, meteorological and remote sensing data are publicly available so that our results could be transferable and comparable with other locations. The land use data for 2000 and 2015 was obtained from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Science (http://english.radi.cas.cn/). This was generated through interpretation of 30 m spatial resolution Landsat TM (https://earthexplorer.usgs.gov/). The land use and land cover types were classified into six categories: forest lands, grasslands, croplands, wetlands, built-up lands and unused land. Other data is described in detail in the following sections.

2.2.1 Provisioning services

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

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

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

2.2.2 Regulating services

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

Soil erosion has had severe issue that significantly impacted on the environmental quality and social-economic development of the Loess Plateau. Therefore, assessments of erosion control under changing land cover are important to understand the efficiency of vegetation restoration (Fu et al., 2011). We first quantified annual potential soil loss using the InVEST Sediment Delivery Model, which is based on the revised universal soil loss equation (RUSLE). Then, actual soil loss was calculated as the annual potential soil loss multiplied by a vegetation cover (C) factor and an erosion control practice (P) factor, which were estimated by using the vegetation cover-based method (Cai, 2000) and the slope-based method (Lufafa et al., 2003), respectively. Finally, erosion control was calculated as soil loss for bare soil (i.e. the potential soil loss) minus that under the current land use and land cover pattern (i.e. the actual soil loss) (Laterra et al., 2012).

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

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

2.2.3 Cultural service

Forest recreation was selected to represent a cultural services in the Loess Plateau due its importance in the process of vegetation restoration. Following previous research methods (Raudsepp-Hearne et al., 2010; Yang et al., 2015), we quantified this indicator from the percent of forest cover (i.e. areas of all forest divided by the total area of the county), as calculated from the land cover maps of 2000 and 2015.

Table 1.

Indicators and methods used to measure each ecosystem service in the Loess Plateau

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	
	Oil crop production (OIL)	Oil yield, t/hm^2	Measurable proxies	Statistical Yearbook	County
	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

2.3. Spatial scale and data summaries

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

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

2.4. Interactions among ESs and delineation of ES bundles

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

3. Results

3.1. Spatial patterns and changes of ESs

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

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

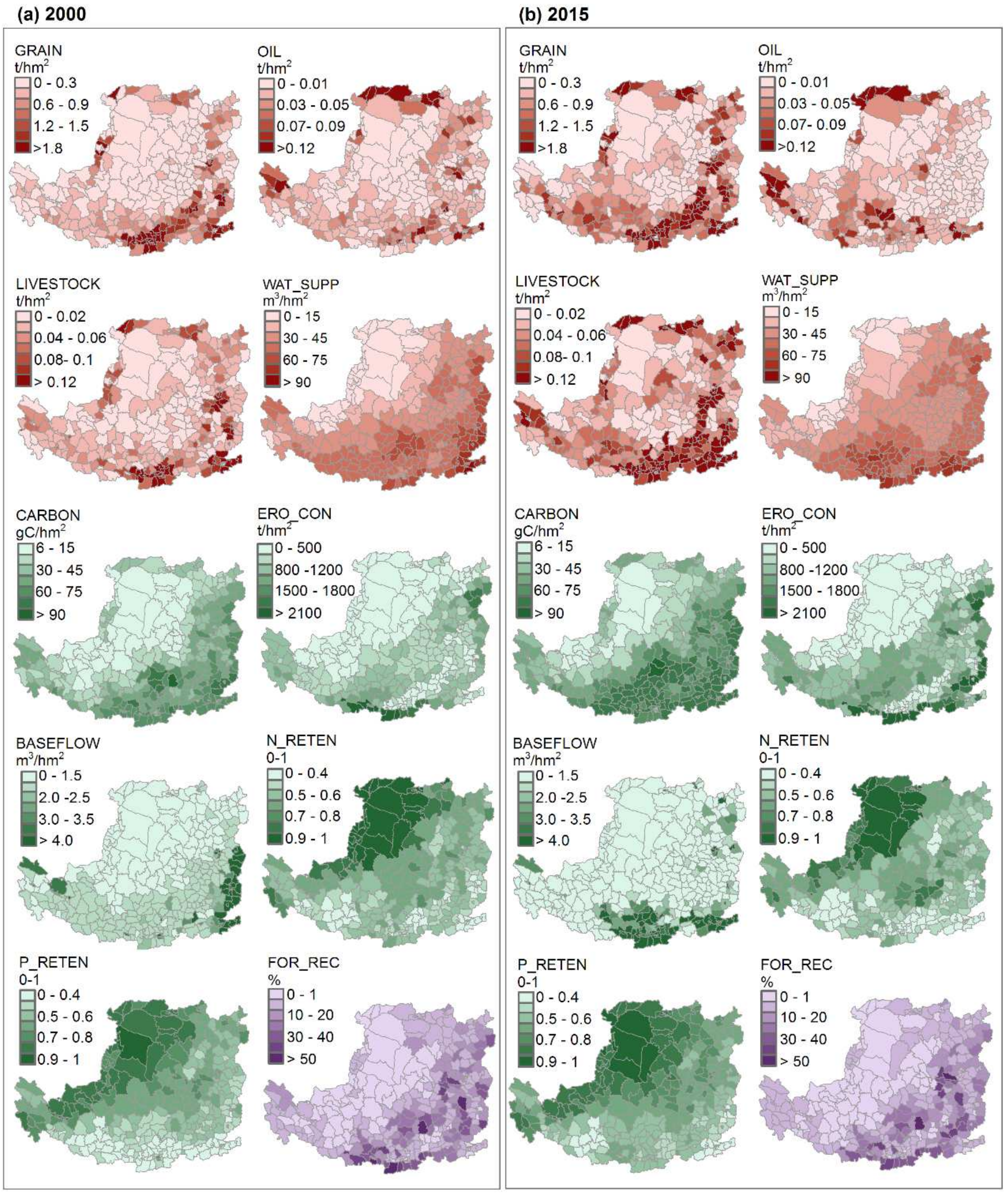

Fig. 2. Distributions of 10 ecosystem services across the Loess Plateau in (a) 2000 and (b) 2015. The values for N and P exports were transformed into ecosystem services for nutrient retention after the standardization and normalization phase, resulting in values describing the capacity for N or P retention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

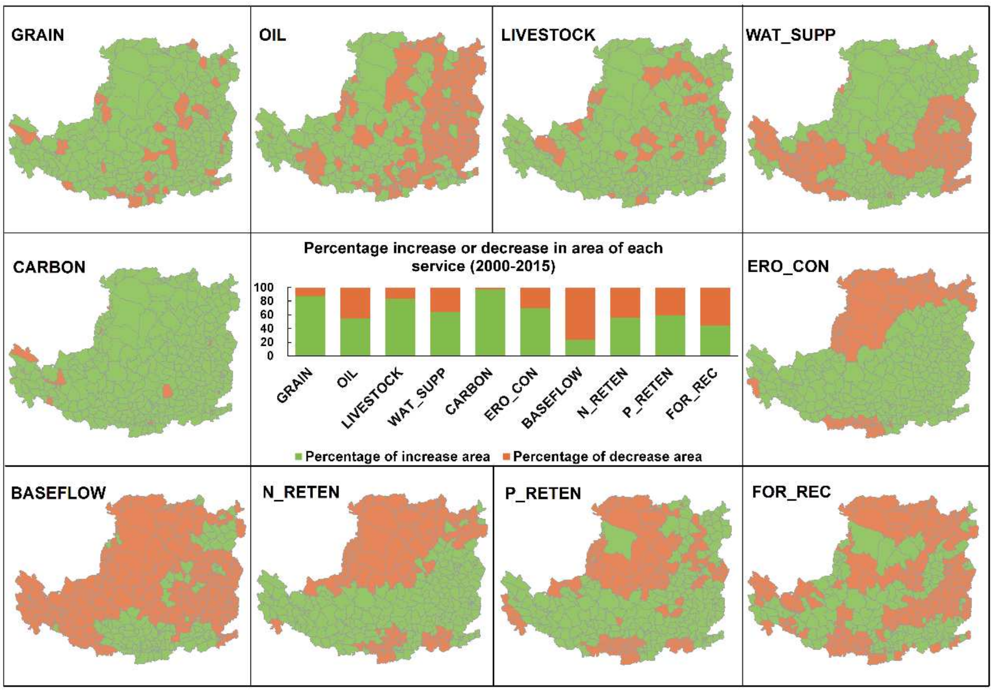

Fig. 3. The increases and decreases in the area of each services at the regional scale. The percentage increase in area indicates higher service values in 2015 than in 2000 and percentage decrease in area indicates lower services values in 2015 than in 2000.

3.2. Trade-offs and synergies among ESs

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

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

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

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

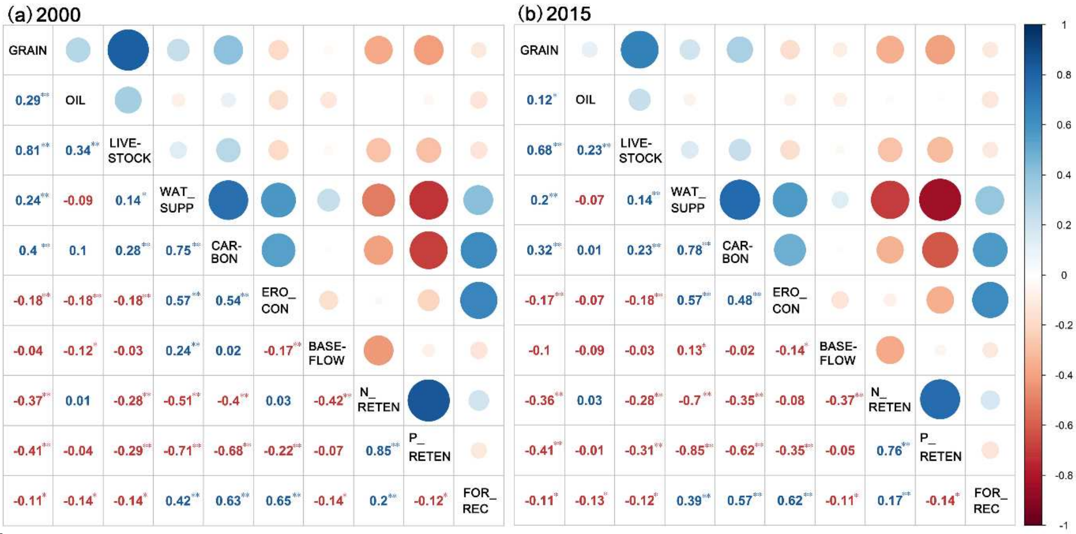

Fig. 4. Pearson correlations between pairs of ecosystem services in (a) 2000 and (b) 2015 (**P* < 0.05; ***P* < 0.01). The lower left part of each figure indicates the Pearson's correlation coefficients (*r*) and the blue and red circle (upper right part) indicate positive and negative correlations,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

3.3. Patterns and changes of ES Bundles

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

Comparison of ES bundles between 2000 and 2015 reinforced the observed spatial heterogeneity of the ten ESs. Gaps between agricultural provisioning services and baseflow regulation with other ESs were more obvious in 2015, although most of the ESs were generally improved. For example, for Cluster 2 and Cluster 3, the high values of water supply and carbon sequestration were strengthened but affected the balance of other ESs compared to 2000 as a consequence. Spatially, the number of counties involved in Cluster 1 and Cluster 2 decreased from 88 and 121 to 67 and 116, respectively, while Cluster 3 and Cluster 4 increased from 71 and 54 to 82 and 69, respectively. The counties in Cluster 1 and Cluster 2 had a northward shift, which were accompanied by transverse expansion in Cluster 3 and Cluster 4 (Fig. 5).

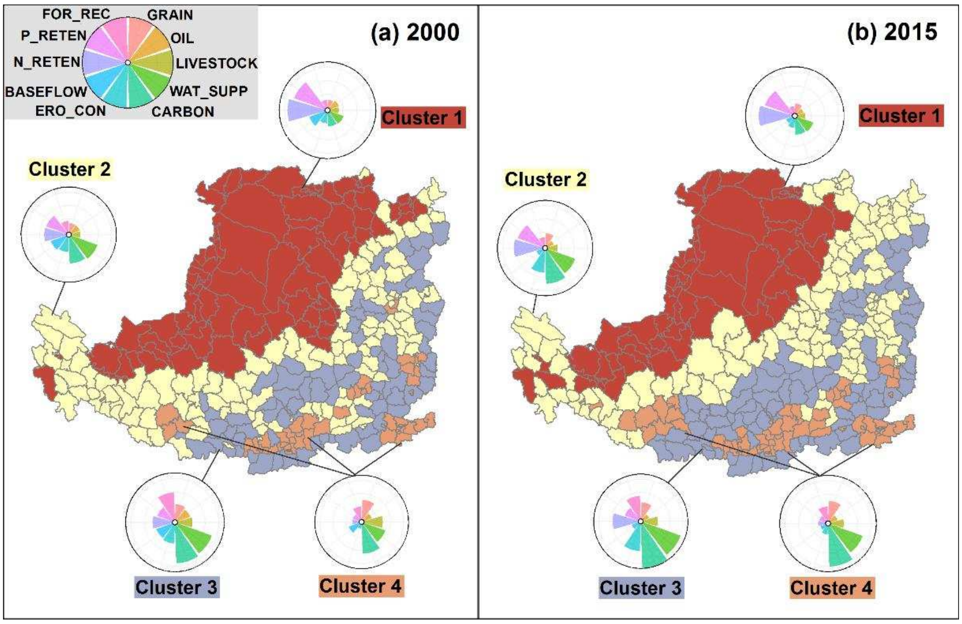

Fig. 5. Ecosystem services bundles in (a) 2000 and (b) 2015. The rose plots represent the average values of ecosystem services detected within each of the clusters. The maps show the spatial distribution of the counties characterized by each ecosystem services bundle.

4. Discussions

4.1. The clustered distributions of ESs

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

4.2. Vegetation restoration is critical for ESs

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

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

The influences of large-scale newly planted vegetation on water resource is more complicated, especially in seasonally dry areas such as the Loess Plateau. Precipitation is the major source of water to ecosystems in the Loess Plateau (Feng et al., 2016; Feng et al., 2013), and was not found to increase or decrease significantly during the period 2000 to 2015. Therefore, the decreases in water supply and baseflow were mainly driven by the increases of vegetation cover in the Loess Plateau. This allowed more evaporation as more precipitation is intercepted by vegetation canopy (Yang et al., 2012), while vegetation transpiration effects also consumed precipitation input. Therefore, re-vegetation increased evapotranspiration but decreased runoff (Feng et al., 2016). In arid and semi-arid watersheds, baseflow is more sensitive to the changing evapotranspiration caused by vegetation-associated shifts (Tang et al., 2016). For the Loess Plateau with thick loess deposits, only a small proportion of infiltrated rainfall is able to recharge groundwater, even though the increased litter layers can favor precipitation infiltration (Zhang et al., 2008). By contrast, re-vegetation caused excessive use of the limited soil water available through plant root uptake, which slowed the infiltration process and offset the potential gains in groundwater recharge (Liang et al., 2015; Ribolzi et al., 2018). Thus, in this study baseflow became more unsteady and showed a large decrease (Fig. 3). Consequently, we recommended that baseflow regulation should be included as a key indicator for a comprehensive understanding of changes in ESs under vegetation restoration programmes.

4.3. The tendency of depressed synergies between ESs

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

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

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

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

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

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

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

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

5. Conclusions

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

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Appendix A. Supplementary materials

Supplementary materials to this article can be found online.

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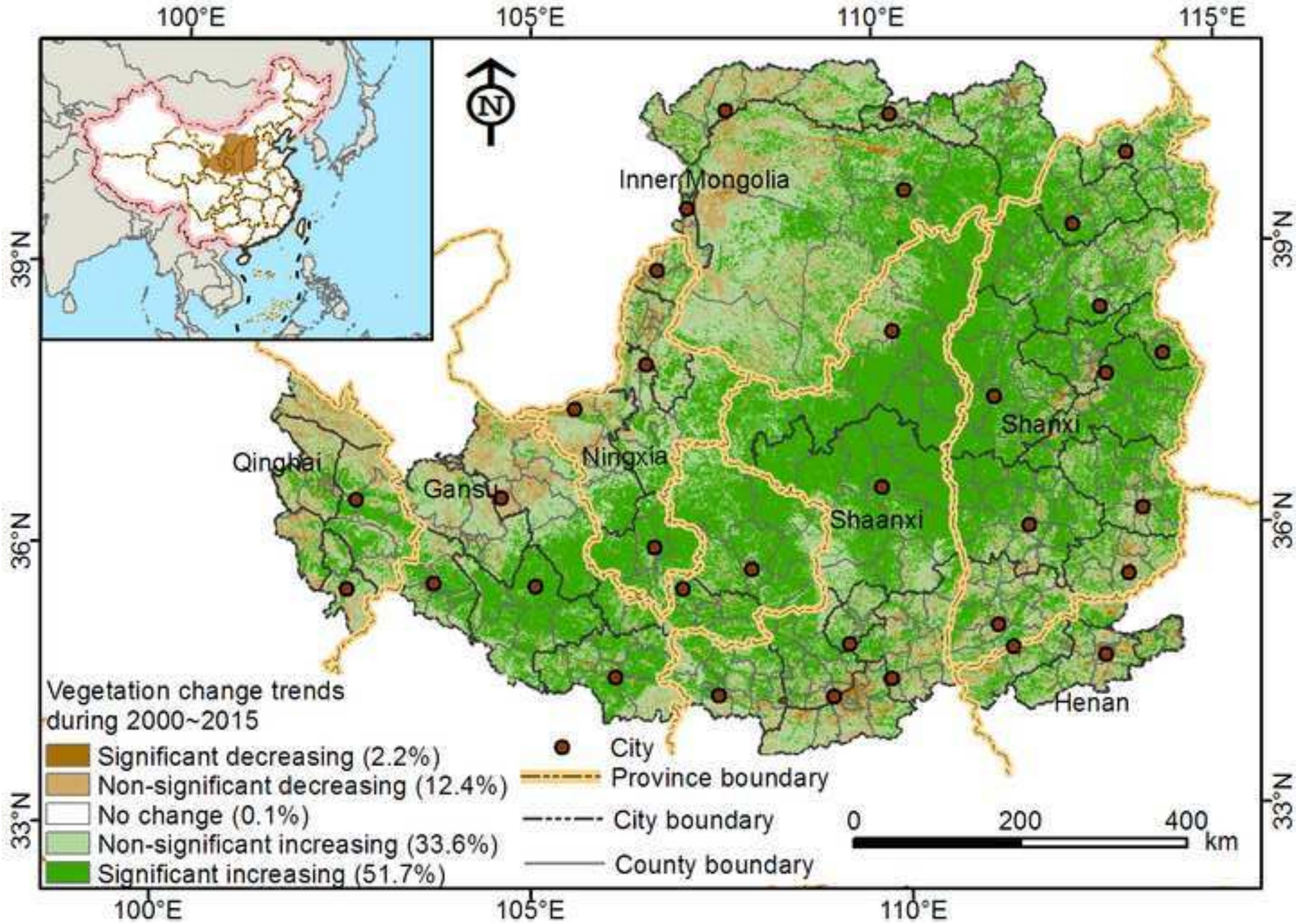

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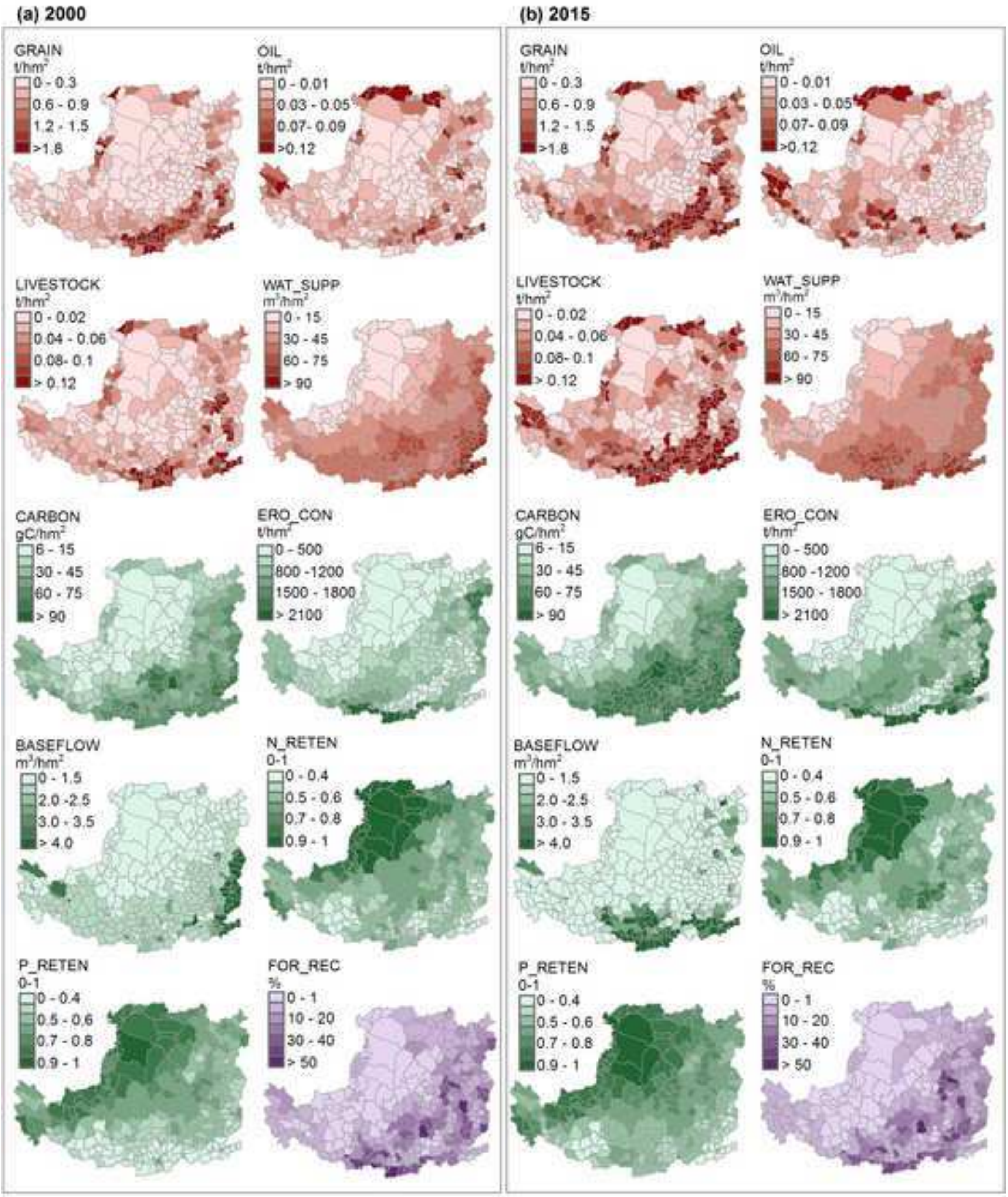

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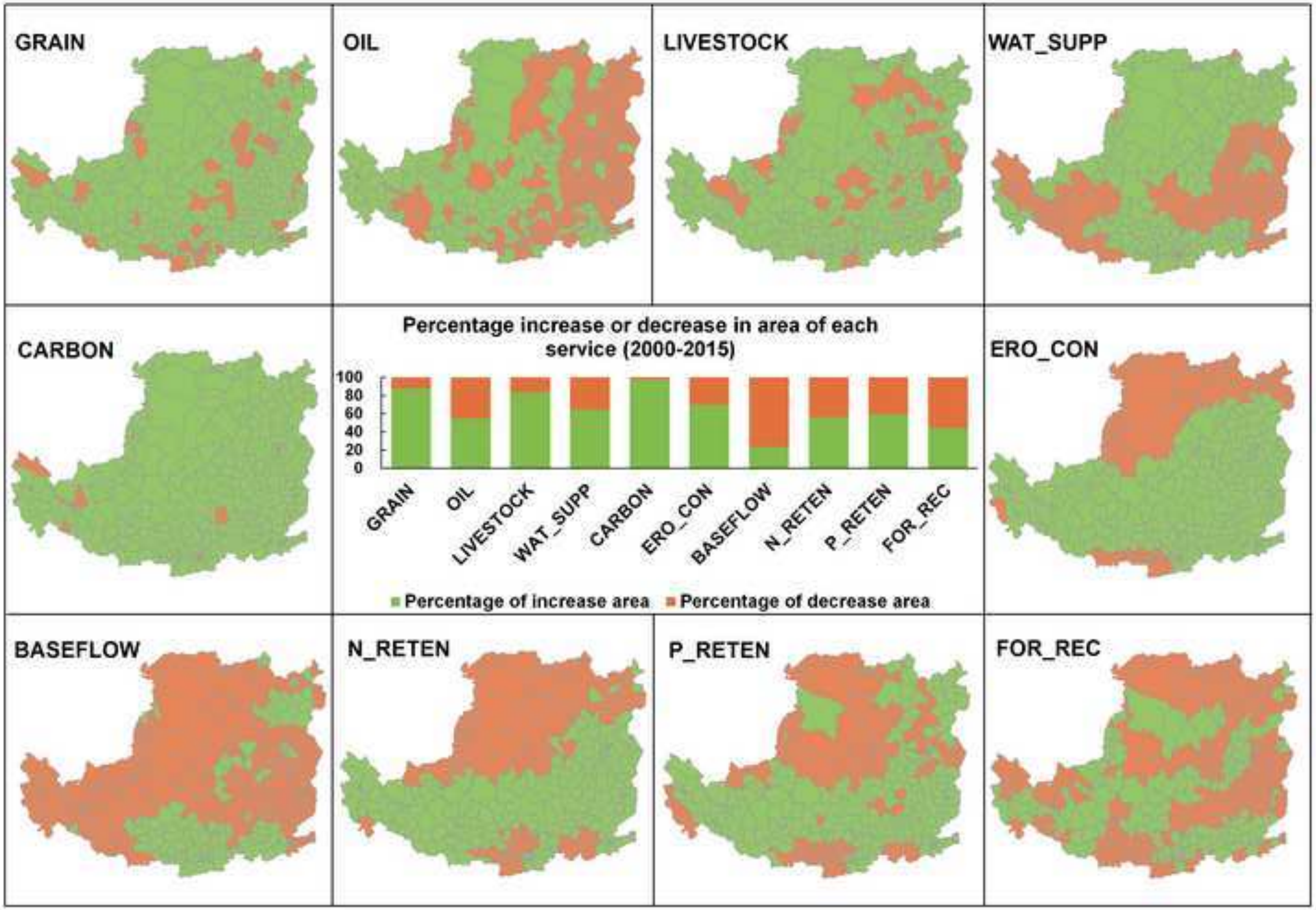

Figure4

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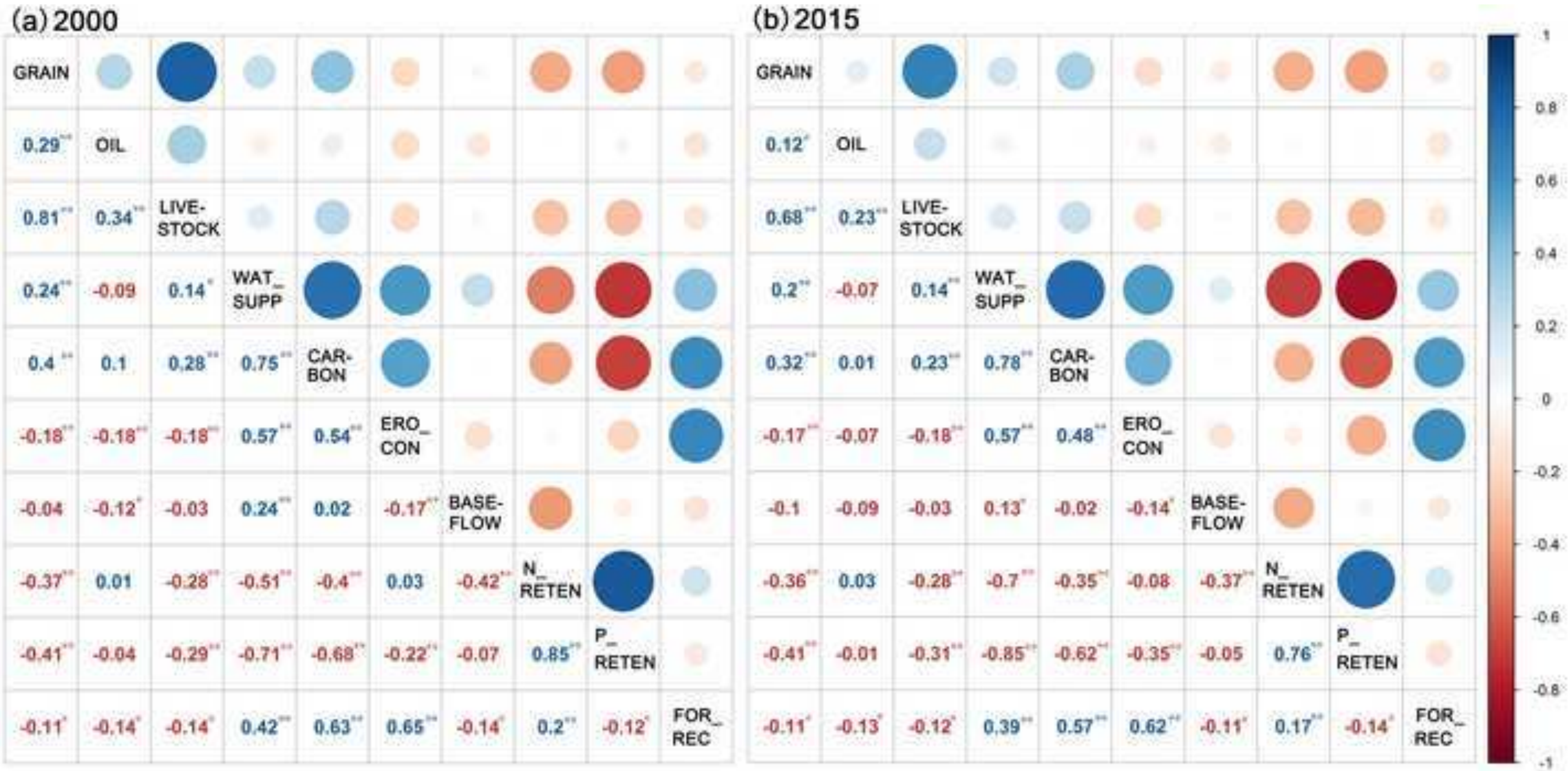

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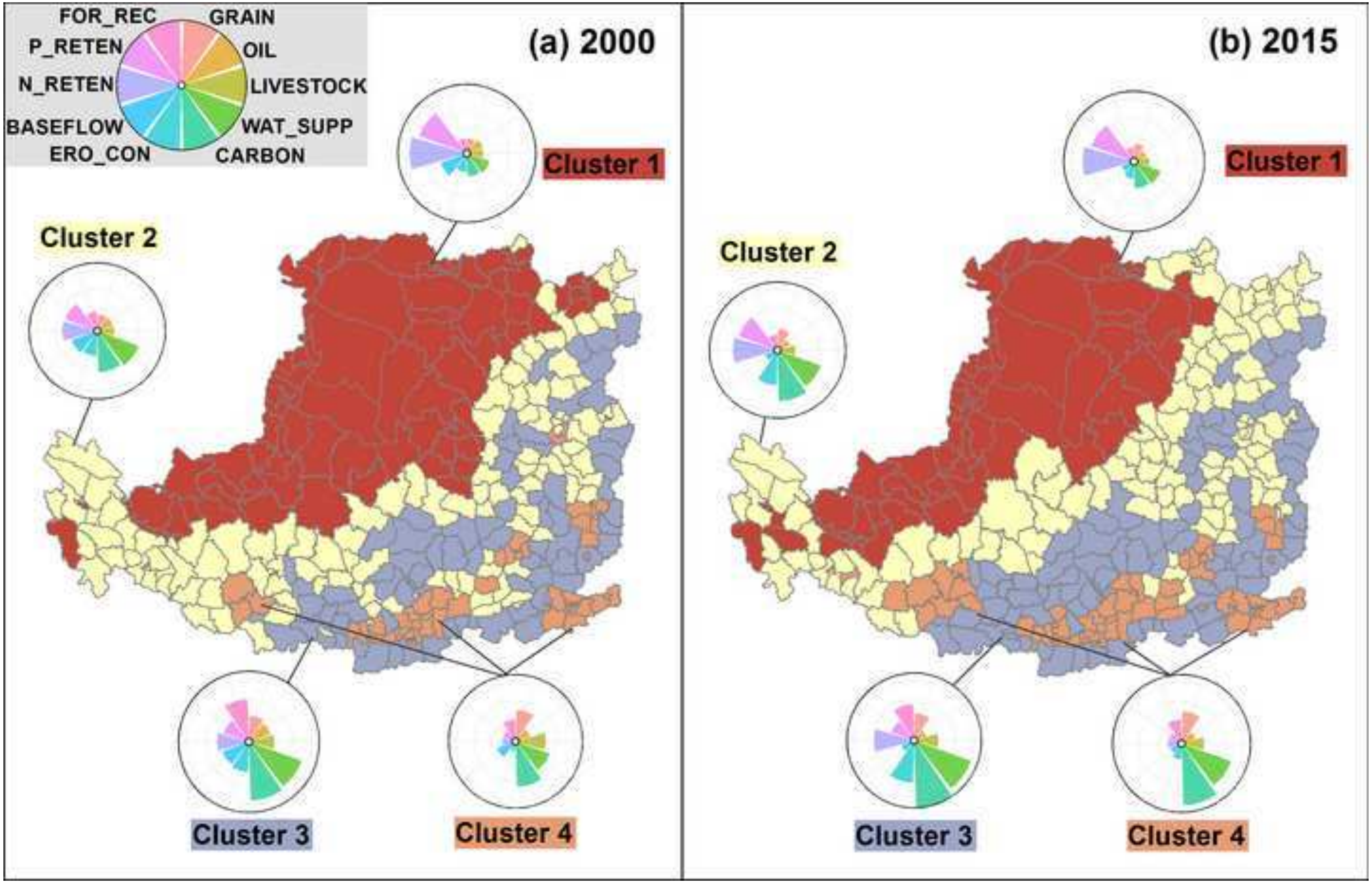

Supplementary Material

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