Investigating Ecosystem Service Trade-offs/synergies and their Influencing Factors: A Case Study in the Yangtze River Delta region of China

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Investigating ecosystem service trade-offs/synergies and their influencing factors: A case study in the Yangtze River Delta region of China

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Abstract

A comprehensive understanding of the trade-off/synergy relationships that exist among multiple ecosystem services (ESs) has become increasingly important for ecological management and sustainable development. However, the determination of the factors that promote trade-off/synergy relationships and the extent to which the driving factors affect these complex relationships have not been well studied, limiting the effectiveness of sustainable ecosystem management. This study employed the Yangtze River Delta region in China as the study area and investigated the spatiotemporal changes in three ESs, namely, carbon storage (CS), water purification (WP), and habitat quality (HQ),

from 2005 to 2015. A trade-off/synergy degree (TSD) indicator was developed that allowed for the quantification of the trade-off/synergy intensity, and the spatial pattern of the TSD between ESs in the YRD region was analyzed. Furthermore, a geographically weighted regression (GWR) model was used to analyze the relationship between the driving factors and trade-offs/synergies. The results revealed that CS, WP, and HQ decreased by 1.17%, 2.49%, and 3.38%, respectively. The TSD indicator showed that the trade-off/synergy relationships and their magnitudes were spatially heterogeneous. The coefficients of the natural and socioeconomic factors obtained from the GWR indicated that their impacts on the trade-offs/synergies vary spatiotemporally. The impact factors had both positive and negative effects on the trade-offs/synergies. The values of R^2 and AIC implied that the selected factors had significant explanatory power for the trade-off/synergy relationships between paired ESs. The findings could improve the understanding of the spatiotemporal dynamics of trade-offs/synergies and their spatially heterogeneous correlations with related factors.

Keywords

Ecosystem service, trade-off/synergy, TSD indicator, driving factor, spatially heterogeneous, Yangtze River Delta region

Declarations

Not applicable

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Conflicts of interest

No

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Cheng Li], [Jie Zhao] and[Wenfu Yang]. The first draft of the manuscript was written by [Cheng Li] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

1. Introduction

Ecosystem services (ESs) refer to the products and services obtained from ecosystems. ESs are the basis of human survival and closely related to human wellbeing. As evidenced by the Millennium Ecosystem Assessment (MEA), the loss of ESs in recent decades directly threatens regional and global ecological security (MEA 2005), and this worsening trend is likely to continue in the future due to the increasing intensity of human activities (Zhou et al. 2018). In the process of pursuing socioeconomic benefits, human beings often neglect the trade-off between ESs, which leads to an improvement in one ES at the expense of other ESs, thus threatening the stability and security of ecosystems and significantly influencing human wellbeing (Feng et al. 2017). Ecosystem management should not only pursue single ecosystem service benefits but also consider the balance among multiple ESs to maximize the overall benefits and promote regional sustainable development. The importance and urgency of understanding the complex interactions among multiple ESs have been widely recognized by ecosystem managers and researchers (Groot et al. 2018; Sherrouse et al. 2017; Xu et al. 2018). Many efforts have been made to describe and assess changes in ESs and their complex interactions (trade-offs and synergies) as well as the urbanization process and land cover changes (Zheng et al. 2016; Lauf et al. 2014; Sherrouse et al. 2017). Previous studies on ESs found that trade-off relationships are ubiquitous (Langner et al. 2017; Darvill and Lindo 2016), for example, consider the trade-off

78 between services resulting in the provision of a good (food production, wood
79 production) and regulation services (soil conservation, water purification, regional
80 biodiversity maintenance). Prior findings suggest that ecosystem management should
81 coordinate various ESs to promote their overall benefits (Landuyt et al. 2016; Feng et
82 al. 2020).

83 The identification of the trade-off/synergy relationships that exist between ESs can
84 improve the effectiveness of ecological management (Goldstein et al. 2012; Baró et al.
85 2017). Over the past few years, numerous studies on trade-offs/synergies have focused
86 on the identification and expression of the types of relationships that exist between
87 multiple ESs using different methods. At present, research involving a trade-off/synergy
88 analysis is mainly conducted using statistical methods (Washbourne et al. 2020; Zhou
89 et al. 2017), spatial mapping (Haase et al. 2012), and scenario analysis (Wu et al. 2019;
90 Asadolahi et al. 2018). For instance, Braun et al (2018) applied Pearson correlation
91 analysis to identify the various types of relationships that exist between ESs; Xu et al
92 (2018) used spatial overlapping and Spearman's rank correlation to analyze the
93 relationships among ESs; Kubiszewski et al (2017) adopted scenario analysis to
94 determine the trade-offs/synergies that exist between ESs; and Zheng et al (2016) used
95 radar graphs to represent the trade-off/synergy relationships. These methods have
96 enhanced the understanding of the trade-offs/synergies that exist among ESs. However,
97 qualitative analyses of the trade-off relationships cannot measure the magnitudes of the
98 effects of the related factors on the trade-off/synergy relationship, which is required for
99 effective ecosystem management and planning (Bennett et al. 2009; Castro et al. 2014).

100 The potential nonlinear characteristics of the trade-offs/synergies between ESs cannot
101 be adequately addressed using qualitative methods. Therefore, quantitative research is
102 urgently needed to analyze the trade-offs that exist among ESs. Some scholars tried to
103 develop indicators to analyze these trade-offs. Laterra et al (2012) used the total
104 ecosystem services (TES) index to quantify the interrelationships that exist among

multiple ESs; Bradford and D'Amato (2012) used the root mean square error (RMSE), a statistical method, to evaluate the trade-off relationships among multiple ESs. Pan et al (2013) quantified the trade-off relationships among ESs by proposing the Ecosystem Trade-off (ETO) index. However, the temporal scale effect of the trade-offs/synergies among ESs was not considered in previous studies. Furthermore, these indicators cannot reveal how the variations in multiple natural and socioeconomic factors affect the interactions between ESs over a specific period. Thus, the quantitative and spatial nature of these trade-offs/synergies is strongly limited.

Fully understanding how influencing factors affect ESs and their trade-offs/synergies is a prerequisite for effective and targeted regional planning (Locatelli et al. 2014). Therefore, it is urgent to identify the factors of the interactions that exist among ES's relationships. By understanding the related factors and their effects on trade-offs/synergies, we can coordinate the trade-offs and improve the synergies between ESs (Zhang et al. 2020). Several studies have argued that the understanding of ES trade-offs/synergies is insufficient without carefully considering and analyzing the driving mechanisms that underlie ES relationships (Dade et al. 2018; Ndong et al. 2020). Although many studies have been carried out to investigate the trade-off and synergy relationships and their spatiotemporal changes, there is still little known about the factors of these complex interactions. The dynamics of ESs and the related trade-off/synergy relationships are complicated processes that involve various natural and socioeconomic variables. In prior studies, the relationships between influencing factors and the associated trade-offs/synergies were commonly analyzed using qualitative methods such as by comparing scenarios (Zheng et al. 2016; Lauf et al. 2014; He et al. 2020). The question of how and to what extent the influencing factors affect trade-offs/synergies remains poorly understood. To address these gaps, in this study, correlation analysis techniques such as Pearson correlation (Zhong et al. 2020), redundancy analysis (RDA) (Feng et al. 2017), and multivariate regression trees

(Ndong et al. 2020) were applied to explain the global relationships among ES trade-offs/synergies and the related factors without considering spatial heterogeneity. It is recognized that the trade-off relationships among ESs are affected by spatial heterogeneity. For example, in South Africa, a trade-off between carbon sequestration and freshwater supply was found (Chisholm 2010), while research on the Baiyangdian River Basin found a synergistic relationship between these two variables (Bai et al. 2013). Global relationships reveal information only about the average conditions and might consequently overlook location-specific impacts (Fotheringham and Brunson 1999; Su et al. 2014). If we ignore spatial heterogeneity, errors might arise in the results of analyses on the impacts of influencing factors on ES interactions, increasing uncertainty about ES management policies (Zhang et al. 2020). It is therefore crucial to explore the spatiotemporally varying relationships between trade-offs/synergies and the related factors.

The Yangtze River Delta (YRD) region is an economically developed and densely populated area in China that is experiencing serious ecological degradation and environmental pollution. This paper aims to partly address this knowledge gap by using the YRD as the study area and investigating the spatiotemporal changes in the trade-offs/synergies among ESs and their spatial heterogeneous correlation with the related factors. Three aspects are of particular interest: (1) the dynamics of trade-offs/synergies that exist among ESs in the YRD region; (2) the spatially heterogeneous relationships that exist between the influencing factors and trade-offs/synergies; and (3) the implications of coordinating ESs to achieve sustainable development for ecosystem management.

2. Material and methods

2.1 Study area

In this paper, the YRD region refers to associated urban agglomeration discussed in the

“Yangtze River Delta Urban Agglomeration Development Plan” approved by the State Council in May 2016. The YRD region is located in a subtropical monsoon climate zone, with annual precipitation of 800-1600 mm. As shown in Fig. 1, the YRD region includes 26 cities, including Shanghai, Nanjing, Hangzhou, Hefei, etc. The area of the whole region is 211,700 km², accounting for 2.1% of the total land area of China.

The YRD region is one of the regions with the most rapid economic and urbanization development in China. Changes in land use have significantly changed the structure and pattern of regional ecosystems, and many ecological environmental risks related to water regulation, air purification, and climate regulation are becoming increasingly severe. Because trade-offs exist between ESs, the increase in the output of food production and wood production have led to the decline of WP and soil and have adversely affected conservation, leisure, recreation and other regulations, support services and cultural services. These problems are the result of the trade-offs that exist between ESs due to the influence of human activities and natural factors. The contradiction between regional socioeconomic development and the protection of the ecological environment has become the main limiting factor that restricts the coordinated development of the YRD region and has a certain negative impact on human wellbeing. Due to socioeconomic development and the expansion of cities, the magnitude of ES trade-offs will continue to increase.

Therefore, the quantitative measurement of the spatiotemporal dynamics in the patterns of the trade-offs/synergies in the YRD and identification of the spatially heterogeneous effects of influencing factors on trade-offs/synergies in the YRD region may not only enrich research on ESs but also provide a scientific basis for optimizing ecosystem management and regional planning.

Fig. 1 The YRD

2.2 Data

The following data were used in this study: (1) Land cover data on the YRD region for 2005 and 2015 with a resolution of 30 m were obtained from the Data Centre for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (<http://www.resdc.cn/Default.aspx>). Land cover was reclassified into six categories based on the data: cultivated land, forestland, grassland, water bodies, built-up land, and unused land. (2) Meteorological data, including information on precipitation, total solar radiation and the temperature in the YRD region from 2005 to 2015, were derived from the China Meteorological Data Service Centre (<http://data.cma.cn/>). (3) Soil property data, including soil depth and the content percentage of sand, clay, silt and organic matter at the scale of 1:1,000,000, were obtained from the Harmonized World Soil Database version 1.1 (HWSD). (4) Digital elevation model (DEM) data for the YRD region with a resolution of 30 m were obtained from the Geospatial Data Cloud

(<http://www.gscloud.cn/>). (5) Socioeconomic data, including information on the gross domestic product (GDP) and population of the YRD region in 2005 and 2015, were obtained from the statistical yearbook of 26 cities in the YRD region. In this study, spatial data were projected to the WGS_1984_Albers coordination system, and all raster data were resampled to a resolution of 100 m.

This study was divided into the following steps: (1) the estimation of ESs; (2) the measurement of the trade-offs/synergies among ESs during the study period; and (3) the estimation of the correlation between trade-off/synergy and multiple related factors. The method used in this study is presented in the following:

2.3 Estimation of ESs

In this study, we identified four key types of ESs with consideration of the following criteria: (1) The selected ESs should be strongly related to human wellbeing in the YRD region. (2) The data needed to calculate the selected ESs should be available. (3) The selected ESs should be significantly influenced by human activities and socioeconomic development. (4) The coordination of the selected ESs should be important for regional sustainable development. Based on these criteria, three key ES indicators were selected for the YRD region: carbon storage (CS), water purification (WP), and biodiversity conservation (BC). These ESs are significantly related to human wellbeing and are important for the ecological environment. Their importance increases in the YRD region due to rapid socioeconomic development.

By using InVEST, the spatial patterns of CS, WP, and BC were quantitatively estimated. The calculations used for the parameters required by the model are shown in Table 1. A carbon storage and sequestration model was used to estimate CS based on four types of carbon pools (aboveground biomass, belowground biomass, the soil and dead organic matter). WP was evaluated in terms of nitrogen export by adopting a nutrient delivery ratio model. A higher nitrogen export value indicates a lower level of WP. BC was

quantified using the habitat quality (HQ) model in InVEST, which considers land cover types and threats (Zhang et al., 2018).

Table 1. Methods and calculations used to estimate the ESs

ES	Method	Formula and variable description
Carbon Storage (CS)	InVEST Carbon Storage and Sequestration model ()	$CS = C_{above} + C_{below} + C_{soil} + C_{dead}$ <p>C_{above}: above ground biomass carbon stocks; C_{below}: below ground biomass carbon stocks; C_{soil}: soil carbon stocks; C_{dead}: dead organic matter carbon stocks. The biomass carbon density for the different land use types was derived from the results of a relevant study (Chuai et al. 2013) (Table A.1)</p>
Water Purification (WP)	InVEST nutrient delivery model	$ALV_x = HSS_x \times pol_x$ $HSS_x = \frac{\lambda_x}{\lambda_w}$ $\lambda_x = \log(\sum_U Y_U)$ <p>ALV_x: adjusted nitrogen export value for pixel x; HSS_x: hydrological sensitivity score for pixel x; pol_x: export coefficient for pixel x. λ_x: runoff index for grid cell x; λ_w: mean runoff index in the watershed; $\sum_U Y_U$: sum of the water yield of grid cell along the flow path above grid cell x. The biophysical parameters for water purification was presented in Table A.2.</p>
Biodiversity Conservation (BC)	InVEST HQ model	$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{rmax}} \right)$ if linear $i_{rxy} = \exp \left(- \left(\frac{2.99}{d_{rmax}} \right) d_{xy} \right)$ if exponential $D_{xj} = \sum_{r=1}^R \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^R w_r} \right) r_y \times i_{rxy} \times \beta_x \times S_{jr}$ $Q_{xj} = H_j \times (1 - D_{xj})$ <p>Q_{xj}: HQ of land-use type j; H_j: the habitat suitability of land-use type j; D_{xj}: total threat level in a grid cell x with land-use type j; r_y: intensity of the threat within the cell y; w_r: relative impact of threat r; β_x: level of accessibility in grid cell x; S_{jr}: sensitivity of land-use type j to threat r; i_{rxy}: impact of threat r from grid cell y on the habitat in grid cell x; d_{xy}: linear distance between grid cells x and y; d_{rmax}: maximum effective distance of the threat. The parameters used in the model were presented in Table A.3.</p>

2.4 Measurement of the trade-offs/synergies among ESs

227 Spearman correlation analysis was employed to explore the relationships among ESs at
 228 the county scale based on changes in the ESs from 2000 to 2015. If the Spearman
 229 correlation coefficient for two services is higher than 0, then a synergistic relationship
 230 exists; otherwise, a trade-off relationship exists.

231 An innovative indicator, the trade-off/synergy degree (TSD), was proposed and applied
 232 to further explore the magnitudes and spatial patterns of trade-off/synergy relationships
 233 among the ESs.

234 The *TSD* indicator for ES *i* and ES *j* ($TSD_{i,j}$) over the periods of t_2 and t_1 was
 235 calculated with Eq. (1):

$$236 \quad TSD_{i,j}^{t_2-t_1} = \begin{cases} 0 & (\Delta ES_i^{t_2-t_1} \times \Delta ES_j^{t_2-t_1} = 0) \\ \sqrt{((\Delta ES_i^{t_2-t_1})^2 + (\Delta ES_j^{t_2-t_1})^2)/2} & (\Delta ES_i^{t_2-t_1} \times \Delta ES_j^{t_2-t_1} > 0) \\ -\sqrt{((\Delta ES_i^{t_2-t_1})^2 + (\Delta ES_j^{t_2-t_1})^2)/2} & (\Delta ES_i^{t_2-t_1} \times \Delta ES_j^{t_2-t_1} < 0) \end{cases} \quad (1)$$

237 where $\Delta ES_i^{t_2-t_1}$ and $\Delta ES_j^{t_2-t_1}$ are the relative changes in ESs *i* and *j* over the period
 238 t_2-t_1 , respectively, and are calculated as follows:

$$239 \quad \begin{cases} \Delta ES_i^{t_2-t_1} = (ES_i^{t_2} - ES_i^{t_1})/ES_i^{t_1} \\ \Delta ES_j^{t_2-t_1} = (ES_j^{t_2} - ES_j^{t_1})/ES_j^{t_1} \end{cases} \quad (2)$$

240 where $ES_i^{t_2}$ and $ES_i^{t_1}$ represent the value of ES *i* at time points t_2 and t_1 ,
 241 respectively. As shown in Eq. (1), if $\Delta ES_i^{t_2-t_1} \times \Delta ES_j^{t_2-t_1} = 0$, then $TSD_{i,j}^{t_2-t_1} = 0$,
 242 implying that no trade-off/synergy relationship exists between ES_i and ES_j . If
 243 $\Delta ES_i^{t_2-t_1} \times \Delta ES_j^{t_2-t_1} > 0$, a synergy relationship exists between ES_i and ES_j , and the
 244 level of synergy can be measured by $\sqrt{((\Delta ES_i^{t_2-t_1})^2 + (\Delta ES_j^{t_2-t_1})^2)/2}$. If $\Delta ES_i^{t_2-t_1} \times$
 245 $\Delta ES_j^{t_2-t_1} < 0$, then a trade-off relationship exists between the two ESs, and the level of
 246 the trade-off can be measured by $-\sqrt{((\Delta ES_i^{t_2-t_1})^2 + (\Delta ES_j^{t_2-t_1})^2)/2}$.

247 Before conducting spatial regression analysis, the global Moran's I index was first
 248 applied to detect the spatial dependence of the trade-offs/synergies among the ESs. At

a given significance level, Moran's I value ranges from -1 to 1. A value closer to 1 implies that the trade-off/synergy relationship in a specific area has a trend similar to that of the surrounding areas. A value closer to -1 suggests that the trade-off/synergy relationship in a specific area has a trend that is dissimilar to that of the surrounding areas. If Moran's I is 0, then the trend of the trade-off/synergy relationship is randomly distributed. The equation used to calculate the global Moran's I is as follows (Anselin 1995):

$$I = N \times (\sum_{i=1}^n \sum_{j=1}^n W_{ij} (Y_i - \bar{Y})(Y_j - \bar{Y})) / ((\sum_{i=1}^n \sum_{j=1}^n W_{ij}) \sum_{i=1}^n (Y_i - \bar{Y})^2) \quad (3)$$

where I is Moran's I index; N is the number of units; Y_i and Y_j indicate the trade-off/synergy values for ES i and ES j ; and $\bar{Y}$ denotes the average level of the trade-off/synergy values of the ESs. W_{ij} represents the row-standardized contiguity matrix.

2.5 Evaluation of the impacts of factors on ESs trade-offs/synergies

With consideration of natural and socioeconomic influences, seven potential influencing factors were selected: elevation (ELE), changes in annual average precipitation (PRE), changes in annual average temperature (TEM), changes in GDP (GDP), changes in population density (POP), and changes in the proportion of built-up land (BUL).

Understanding how the influencing factors have contributed to the variations in the trade-offs/synergies among ESs is crucial for effective ecosystem management. Multiple linear regression (MLR) is one of the regression methods commonly used for exploring the relationships between multiple explanatory factors and independent variables (Yu et al. 2020). Taking the study area as a whole, MLR can be used to explore the average regression coefficient by identifying a global relationship. The MLR used in this study is expressed in Eq (4):

$$y_i = \beta_0 + \sum_{k=1}^i \beta_k x_{ik} + \varepsilon \quad (4)$$

274 where y_i is the estimated TSD value; β_0 and β_k represent the intercept and
 275 regression coefficients of independent variable k , respectively; x_{ik} is the value of
 276 independent variable k at unit i ; and ε is the random error term for unit i .

277 A geographically weighted regression (GWR) model can estimate a location-specific
 278 regression coefficient for each unit in the study area by considering spatially varying
 279 relationships that exist between the dependent and independent variables. In this study,
 280 a GWR model was adopted to investigate the relationships between the related factors
 281 and the trade-offs/synergies while considering spatial heterogeneity. The formula used
 282 for the GWR is similar to that used for the MLR, except the former takes spatial
 283 heterogeneity into consideration. The GWR can be expressed as follows (Fotheringham
 284 et al. 1997):

$$285 \quad y_i = \beta_0(u_i, v_i) + \sum_{k=1}^i \beta_k(u_i, v_i)x_{ik} + \varepsilon_i \quad (5)$$

286 where y_i represents the TSD value for unit i ; (u_i, v_i) represents the coordinates of
 287 unit i ; $\beta_0(u_i, v_i)$ is the constant term estimated for unit i ; and $\beta_k(u_i, v_i)$ is the
 288 estimated regression coefficient of factor k at unit i . x_{ik} represents the value of
 289 independent variable k that could explain TSD at unit i ; ε_i is the random error term
 290 for unit i . The regression coefficients of each unit are estimated by weighting all units
 291 around unit i . The units closer to unit i have a stronger impact on the estimated
 292 coefficient. The Gaussian kernel was selected to calculate the spatial weighting:

$$293 \quad w_{ij} = \exp\left(\frac{-d_{ij}^2}{h^2}\right) \quad (6)$$

294 where w_{ij} is the weight of unit j for unit i . d_{ij} represents the Euclidean distance
 295 between unit i and unit j . h is the kernel bandwidth, which determines the range of
 296 spatial dependency. In this study, we selected the optimal bandwidth identified by the
 297 Akaike's information criterion (AIC) method for the purposes of minimizing the AIC
 298 value: the estimated results with lower AIC values better reflect reality.

The performance of the regression models (MLR and GWR) can be measured and compared by considering R^2 and AIC. R^2 is the square of the correlation coefficient, indicating the degree of agreement between the estimated value and the observed value. AIC is not an absolute goodness of fit, but it can be used to effectively compare several different models. A difference between the AIC values of two models higher than 3 suggests that there is a significant difference between the two models. A more suitable model, which is assessed by its capability to better explain the variations in the dependent variables, tends to have a higher R^2 and lower AIC.

3. Results

3.1 Spatial patterns of ESs

As shown in Fig. 2, forestland is mainly located in the southern part of the YRD region. High-intensity built-up land is concentrated along the Yangtze River. Cultivated land is mainly distributed in the northern part of the YRD region. Cultivated land accounted for 47.63% of the total area, the largest proportion of the YRD region, in 2015. Built-up land accounted for 12.75% of the total area in 2015.

From 2005 to 2015, built-up land increased by 7760.21 km², which accounted for the largest proportion of change in land cover. In contrast, cultivated land, forestland, grassland and wetland decreased. Cultivated land decreased significantly from 107,224.31 km² to 100,253.03 km² over ten years due to rapid urbanization. A large proportion of the decrease in cultivated land was caused by newly developed built-up land. Forestland and wetland decreased by 502.03 km² and 400.31 km² from 2005 to 2015, respectively.

Fig. 2 Land cover map of the YRD region in 2005 and 2015.

Table 2. Area of various land cover types in the YRD region in 2005 and 2015 (km²).

	Cultivated land	Forestland	Grassland	Wetland	Built-up land	Unused land
2005	107224.31	57424	7377.18	19340.63	19072.64	34.16
Proportion	50.94	27.28	3.51	9.19	9.06	0.02
2015	100253.03	56922	7291.3	18940.32	26832.85	233.45
Proportion	47.63	27.05	3.46	9.00	12.75	0.11
2005-2015	-6971.28	-502.03	-85.88	-400.31	7760.21	199.29

Along with land cover changes in the YRD region, the selected ESs also varied over the study period. The overall magnitude of CS, WP (measured by nitrogen export), and BC (measured by HQ) in the YRD region decreased from 2005 to 2015. CS decreased marginally from 5.028×10^8 to 4.969×10^8 Mg. The total amount of WP decreased from 3.891×10^7 kg to 3.794×10^7 kg. The average value for BC shows a declining trend, with the value decreasing from 0.385 in 2005 to 0.372 in 2015.

Table 3. The total amount of ESs in the YRD region in 2005 and 2015.

	CS (Mg)	WP (kg)	BC
2005	5.028×10^8	3.891×10^7	0.385
2015	4.969×10^8	3.794×10^7	0.372
2005-2015	-1.17%	-2.49%	-3.38%

There is significant spatial heterogeneity in CS, WP, and BC in 2005 and 2015. As shown in Fig. 3, the high-provision areas for CS were mainly distributed in the southern mountainous area of the YRD, while the lower CS values were located in urban areas, where a large amount of non-built-up land had changed to built-up land. The high-provision areas for WP were mainly distributed in the northern area. WP in the YRD shows a gradual decreasing trend from southeast to northwest, which is consistent with the spatial patterns of the proportion of cultivated land. High values of BC were found in the south areas, which are at higher elevations, while low value areas were mainly distributed in the north area. This result can be explained by the fact that areas with high elevations are mountainous with dense vegetation and rich biodiversity. In these areas, the natural environment, such as mountains, face fewer threats.

Fig. 3 Spatial patterns of ESs in the YRD region at the grid scale (CS: carbon storage; CP: crop production; WP: water purification; BC: biodiversity conservation).

The majority of counties (157 out of 160 counties) in the YRD region show a decreasing trend in CS from 2005-2015 (Fig. 4). Among these cities, Kunshan (Suzhou city) and Jiading (Shanghai city) experienced the most significant decline in average CS,

decreasing by 17.831 Mg/ha and 15.236 Mg/ha, respectively. Dafeng, Xiaoshan, and Chongming showed a slight increase in average CS over the study period.

Overall, WP exhibited a downward trend across the YRD region. At the county level, over one-half (89) of the counties in the YRD region showed that WP is increasing, mainly in the eastern part of the YRD, accounting for 52.8% of the total area. Cultivated land was converted to BUL. The counties exhibiting a significant decrease in WP are the southeastern part of the YRD, including Wenling, Yuhuan, and Huangyan, which implies that nitrogen exports decreased remarkably over time.

Most of the counties (156) presented a declining trend for BC, especially the Suzhou city core and Xiaoshan (Hangzhou city), decreasing by 33.3% and 18.3%, respectively. Only 4 counties experienced an increase from 2005-2015, mainly centralized in Nantong, Chuzhou, Yangzhou, and Taaizhou cities, accounting for 4.43% of the total area. The reduction in BC was mainly due to significant urban expansion.

Fig. 4 Spatial patterns of ES variations at the county scale in the YRD region (CS: carbon storage; CP: crop production; WP: water purification; BC: biodiversity conservation).

3.2 Spatiotemporal dynamics of ESs trade-offs/synergies

We used Spearman correlation analysis to identify the trade-off/synergy relationships that exist among multiple ESs. As shown in Fig. A.1, both trade-offs and synergies were observed. We found that all three pairs of ESs (CS-WP, CS-BC, WP-BC) showed

significant positive or negative correlations ($P < 0.01$). CS was significantly positively correlated with BC. This result was supported by our findings that CS increased from 2005 to 2015, and BC decreased over this period. The trade-offs between CS/WP and WP/BC suggested that a decrease or increase in one ES could lead to an increase or decrease in another ES in a specific county. CS had a strong and significant synergy with BC, with a Spearman correlation coefficient larger than 0.7.

The TSD indicator was further applied to reveal the spatial distribution and magnitude of the trade-off/synergy relationships among the ESs. In contrast to the results of the Spearman correlation analysis, in this analysis, both trade-off and synergy relationships were detected between paired ESs. The spatial distributions of the trade-offs/synergies were significantly heterogeneous (Fig. 5).

Fig. 5 Spatial patterns of the synergies and trade-offs (measured by TSD) among multiple ESs at the county scale in the YRD region (CS: carbon storage; CP: crop production; WP: water purification; BC: biodiversity conservation).

The negative TSD value for CS-WP were mainly distributed in the eastern and southwestern areas, which indicates that a decrease in CS could lead to an increase in WP in these regions. This result is consistent with the previous findings of Bai et al. (2020). A larger amount of ecological land, the main type of land that supports CS, was occupied by built-up land due to the rapid development in this region. Significant urban expansion resulted in a decrease in CS. The loss in ecological land led to an increase in

nitrogen export. Furthermore, the TSD value for CS-WP decreased gradually from the eastern area to the southwestern area. In contrast, the relationship between CS and WP is synergetic ($TSD > 0$) in the southeastern and northwestern areas, and this result contrasts with the implications of the Spearman correlation coefficient for CS-WP. This result suggests that a decrease in CS might decrease nitrogen export. This decrease may have occurred because cultivated land was converted to built-up land, and the increase in built-up land area might decrease CS. Additionally, the higher proportion of built-up land produced higher nitrogen loads than other land cover classes.

CS and BC mainly exhibited a synergistic relationship throughout the YRD region; this relationship can be attributed to high consistency in the land cover types of CS and BC. For example, ecological land normally has higher values of CS and BC. However, built-up land has a lower capacity for CS and BC. The high values for TSD were mainly distributed in the eastern part of the YRD region, and the values gradually decreased from the eastern area to the western area of the YRD region. The Shanghai and Suzhou-Wuxi-Changzhou regions in the eastern area of the YRD region are the most developed areas and exhibit a significant increase in built-up land to meet increasing demand for socioeconomic development. Therefore, the trade-off intensity in this area is higher than in other areas.

Similar to the spatial distribution of the TSD value for CS-WP, a large proportion of counties exhibited trade-off relationships between WP and BC in the eastern and southern areas of the YRD region, which means that the increase in nitrogen export might decrease HQ. In addition, the trade-off intensity gradually decreased from the eastern areas to the southern areas. This decrease may have occurred because newly cultivated land occupies a large amount of ecological land, which leads to a decrease in BC and an increase in WP. Positive TSD values are observed in the northwestern and southeastern areas, which indicates that the relationship between WP and BC is synergistic. When WP decreases, BC will decrease.

The global Moran's I for the TSD of each paired ES is presented in Table 4. The values of 0.8309, 0.3979, and 0.7216 for CS-WP, CS-BC, and WP-BC, respectively, suggest that the patterns of the trade-off/synergy relationships between the paired ESs were spatially autocorrelated.

Table 4. Global Moran's I of the TSD values between paired ESs.

Pairs of ESs	Moran's I	z-score	p-value
CS-WP	0.8309	11.5593	0.0000
CS-BC	0.3979	5.6219	0.0000
WP-BC	0.7216	10.0640	0.0000

3.3 The impacts of related factors on the trade-offs/synergies between ESs

We applied the MLR and GWR models to investigate the spatial relationships between the TSD and seven natural and socioeconomic factors (ELE, PRE, TEM, GDP, POP, and BUL). As shown in Table 5, the R^2 values of the GWR results are larger than those of the MLR model. The AIC values of the GWR are smaller than those of the MLR model. In contrast to the results of the MLR model, which is a global model for estimating the relationship between two variables, the GWR results provide a specific coefficient for each unit. The effects of the spatial relationship between the explanatory and dependent variables on the trade-offs/synergies between the ESs is explored.

Table 5. R^2 and AIC values for the GWR and MLR models

Factors	Indicator	CS-WP		CS-BC		WP-BC	
		MLR	GWR	MLR	GWR	MLR	GWR
ELE	R^2	0.0137	0.8031	0.0981	0.3950	0.0213	0.7643
	AIC	29.9511	-148.1661	-55.1897	77.0673	-4.8324	-165.4915
PRE	R^2	0.5777	0.7456	0.0071	0.3093	0.6076	0.7444
	AIC	-105.7788	-163.5704	-39.8081	-74.5886	-151.0859	-197.8709
TEM	R^2	0.0279	0.7900	0.0063	0.2966	0.0420	0.7538
	AIC	27.6261	-162.3956	-39.6942	-75.4645	-8.2591	-187.0395
GDP	R^2	0.0659	0.7732	0.0713	0.3445	0.0583	0.7658
	AIC	21.2469	-140.3177	-50.5173	-79.4526	-10.9957	-168.7866
POP	R^2	0.0255	0.7697	0.0744	0.3252	0.0098	0.7538
	AIC	28.0298	-132.7592	-51.0407	-74.8401	-2.9728	-155.6341

BUL	R ²	0.1786	0.8640	0.7864	0.8055	0.1597	0.8170
	AIC	0.6776	-203.8839	-285.6687	-290.4239	-29.2331	-193.8583
FOR	R ²	0.0789	0.8606	0.0081	0.3710	0.0930	0.7789
	AIC	19.0150	-163.1552	-39.9697	-83.4644	-17.0035	-162.4327

Fig. 6 presents the spatial distributions of the estimated regression coefficients of the influencing factors and trade-offs/synergies between paired ESs using the GWR model. The effects of the explanatory factors on ES trade-offs/synergies varied spatially. Both positive and negative coefficients are observed in the GWR results. A positive coefficient indicates that growth in the explanatory variable could increase the TSD value. In other words, the probability that the ES relationship will become more synergetic will increase when the coefficient is positive. However, a negative coefficient suggests that a decrease in the dependent variables could decrease the probability that a synergistic relationship exists between the ESs, as evidenced by a declining TSD value.

Elevation was positively correlated with the trade-off/synergy relationships between CS and WP in the eastern part of the YRD region. This result implies that an increase in elevation could enhance the synergy between CS and WP or reduce their trade-off relationship in this area. In contrast, a negative effect of elevation was mainly observed in the western area.

448

449 Fig. 6 Coefficients of the relationship between the TSD of paired ESs and six variables using
 450 the GWR model.

For a large area of the YRD region, there was a negative association between elevation and the CS-BC relationship, which suggests that a decrease in elevation could lead to an increase in synergy intensity. This result may be related to the distribution of ecological land across different elevations. When there is a decrease in elevation, the proportion of forest decreases and that of cultivated land and built-up land increases. The urban expansion rate in this area is relatively higher than that in areas in higher elevations. The changes in CS and BC are relatively significant; thus, synergy was enhanced.

Precipitation is an important variable of the trade-off/synergy relationships from 2005-2015 (Fig. 6). Changes in precipitation had a negative effect on CS-WP and WP-BC. This result implies that an increase in precipitation may either increase the trade-off intensity or reduce the synergy intensity. The vegetation coverage area increased as precipitation increased, CS and BC were enhanced, and WP decreased; thus, trade-off intensity increased. Additionally, the effects of precipitation in the southern area of the YRD region are greater than those in other areas due to its higher proportion of ecological land and significantly higher levels of precipitation. The negative correlation between precipitation and the trade-off/synergy intensity for CS-BC in the southern area was related to the relatively slow changes in CS and BC.

The changes in TEM also had significant effects on the trade-off/synergy relationships between the paired ESs. Both positive and negative correlations between the temperature and TSD were found across the YRD region. As presented in Fig. 6, the spatial distributions of the coefficients for CS-WP and WP-BC are similar. The change in TEM in the eastern and western areas exhibited a negative correlation with the trade-off/synergy intensity of CS-WP and WP-BC. TEM had a positive effect on the TSD in the central and northern areas of the YRD region. As evidenced by Singer (2003), the effects of climate factors on ESs are spatially heterogeneous.

As illustrated in Fig. 6, GDP and POP have positive and negative correlations with the trade-offs/synergies between ESs. CS-WP, CS-BC, and WP-BC have significant positive relationships with GDP and POP in the western area of the YRD region, where the intensity of human activity and the socioeconomic level are relatively weak compared those in with the eastern region. In the eastern area of the YRD region, however, an increase in GDP or POP will increase the probability that the relationships will convert to a trade-off.

The results for R^2 indicate that BUL had the largest effects on the relationships between paired ESs among these factors. The changes in built-up land are negatively correlated with CS-WP and WP-BC relationships in the eastern area of the YRD region, where built-up land is concentrated and increased significantly over the study period (Fig. 6). The newly expanded built-up land occupied a larger amount of cultivated and ecological land, which led to a significant decline in CS and BC because of the loss of land cover classes that support CS and BC. In contrast, urbanization was positively correlated with nitrogen export due to heavy pollutant loads on impervious surfaces and the weak purification ability of the limited amount of vegetation coverage. In addition, BUL exhibited a positive correlation with the synergy intensity of CS-BC across the YRD region, and its effects gradually increased from southern areas to northern areas. This result implies that the synergy between CS and BC is more sensitive to changes in BUL. CS and BC are affected by a higher level of land-use consistency, and the increase in BUL could decrease the area of land cover types that support CS and BC.

4. Discussion

4.1 Spatially varying trade-offs/synergies among the ESs and the underlying factors

By understanding the spatial patterns of the ES relationships' responses to influencing factors, decision makers can regulate these factors to improve the synergy intensity and reduce unwanted trade-offs (Cord et al. 2017). Our findings show that the trade-offs

and synergies among multiple ESs (CS, WP, and BC) were widespread in the YRD region, which is in accordance with the findings of previous studies (Bai et al. 2020; Xu et al. 2018; Jopke et al. 2015). However, studies concerning the spatial distribution of the intensity of trade-offs/synergies are scarce. Pairwise correlation coefficients are commonly used to reveal the global relationships between paired ESs (He et al. 2020; Morán-Ordóñez et al. 2020). This type of analysis reflects only the magnitude of a relationship and does not provide insight into the spatial patterns of a relationship. The hot spots of various ESs were compared to investigate the spatial relationship between two ESs. However, the results generated by hot spot comparisons do not indicate where trade-offs and synergies exist. The RMSE indicator was widely adopted in previous studies to measure the intensity of trade-offs for one temporal point (Bradford and D'Amato 2012; Langner et al. 2017), but changes in ESs over time are not considered in this indicator. Zhang et al (2020) used a binary value (0,1) to measure the relationship by comparing the changes in ESs between two points in time. Although this type of analysis can identify the ES relationships, the magnitude of the relationships is not measured. Therefore, it is difficult to fully reveal the impact mechanisms of the trade-offs/synergies. In this study, we proposed a new indicator (TSD) to quantify the intensity of the trade-off/synergy relationships among ESs and their spatial heterogeneity rather than their spatial homogeneity. Compared with the findings of previous studies, our findings clarify the locations where trade-offs/synergies existed and their intensity.

Our study supports the argument that the relationships between ESs can be affected by natural and socioeconomic factors (Syrbe and Walz 2012). For appropriate ES management, decision makers should consider not only global correlations but also the spatial heterogeneity of the impacts to mitigate unwanted ES trade-offs. In contrast to the findings obtained by using correlation analysis and a global regression model (Feng et al. 2020; Zhong et al. 2020), our results obtained by the GWR model can reveal the

spatial relationship between trade-offs/synergies and the related factors. The intensity of trade-off/synergy relationships was significantly affected by natural factors and socioeconomic factors. A larger number of studies have confirmed that ESs are correlated with urbanization (Baró et al. 2016). Su et al (2014) argued that the effects of urbanization on ESs are spatially heterogeneous, with the magnitude of the effects varying spatially, which is similar to our findings. However, previous studies considering topics related to the effects of influencing factors on the complex relationships that exist among multiple ESs were limited by the use of a global regression model and correlation analysis without considering spatial non-stationarity. In this study, goodness of fit tests employed to compare the MLR and GWR models were assessed using R^2 and AIC. The results indicate that the GWR model has strong explanatory capability for estimating the relationships between the influencing factors and the trade-off/synergy intensity of ESs. The coefficients estimated by the GWR model correspond to a specific geographic area, and the spatially varying effects of various factors can be explored through the creation of a spatial distribution map of the GWR coefficients.

4.2 Policy implications

Integrating information about the trade-offs/synergies between ESs into ecological planning and management is a prerequisite for coordinating the relationship between ecological protection and socioeconomic development (Peng et al. 2017). This study quantitatively explores the influencing mechanisms of natural and socioeconomic processes on the trade-off/synergy relationships among ESs, which is helpful for developing scientific and effective ecosystem service management practices and regional planning. Recommendations for ES regulation and promotion that correspond to our results are as follows:

First, in the context of the collaborative development of the YRD region, it is crucial to

enhance the implementation of precisely targeted ecological projects and refine ecological management policies based on the analysis of the trade-offs/synergies among ESs. In recent years, a range of ecological projects have been carried out, such as the Grain for Green Project, the Natural Forest Protection Project, and Reclaiming Lake from Farmland (Gao et al. 2019). These ecological projects play a key role in enhancing the ecological functions of regional water conservation and soil and water conservation and accelerating the construction of a green ecological corridor in the YRD region. However, ES degradation was still observed in some ecologically sensitive and rapidly developed areas. The YRD region still faces a great challenge in achieving the ‘win-win’ goal of socioeconomic development and ecological protection. Reaching this goal may be difficult because the trade-off/synergy relationships and their spatial heterogeneity and impact factors have been neglected in ecological projects. Therefore, it is important to integrate the complex interactions among ESs into the design and implementation of various ecological projects to promote the efficiency of ecological protection and restoration.

Second, our findings reveal the specific regions where trade-off/synergy relationships exist, which is helpful information for decision making regarding trade-offs in specific locations and implementing ES management more effectively. The YRD region can be separated into three areas based on the intensity of land development, population concentration and changes in ESs: optimized development area, key development area and restricted development area. Different development strategies should be developed for various areas. The optimized development area refers to the area where the carrying capacity of resources and environment is saturated. This area is mainly distributed in Shanghai, Hangzhou, and southern Jiangsu. We should take effective measures to strictly control the scale and intensity of new construction land and appropriately expand agricultural and ecological spaces. The key development area refers to the area with great potential for the carrying capacity of resources and the environment. This

area is mainly distributed in central Jiangsu, central Zhejiang, central Anhui and the coastal area. It is necessary to strengthen the capacity of industrial and population agglomeration, appropriately expand industrial and urban spaces, optimize the rural living space, and strictly protect the green ecological space. The restricted development area refers to the area with significant ecological sensitivity and a low carrying capacity of resources and the environment. This area is mainly distributed in northern Jiangsu, western Anhui and western Zhejiang. It is necessary to strictly control the scale of new construction land; promote the concentrated development of cities; strengthen the protection of water resources, ecological restoration and construction; and maintain the stability of the ecosystem structure and its functioning.

Third, the land development intensity in the YRD region was 17.1% in 2013, which was 15% higher than that due to Japan's Pacific coastal urban agglomeration, and the potential space available for subsequent construction is insufficient. Shanghai's development intensity is as high as 36%, far more than that of Paris at 21% and that of London at 24%. Due to extensive and unrestrained development, new development zones and industrial parks occupy too much land, which seriously affects the overall ecosystem structure and utilization efficiency of regional land space (Xu et al. 2020). Therefore, the “three red lines” (Ecological Protection Red Line, Cultivated land Protection Red Line, and Urban Development Boundary Red Line) policy for spatial planning was proposed to improve land-use efficiency (He et al. 2018). Despite the common acknowledgements of the importance of the three red lines in sustainable development, there are several issues that need to be addressed, including the lack of consideration of the trade-off relationships that exist among ESs, when identifying the three red lines. The establishment of the three red lines could lead to an ES trade-off, where one ES is promoted at the expense of other ESs.

4.3 Limitations and further study

Although this study obtained some interesting findings, some limitations exist. First, trade-off/synergy research and ES management are based on the accurate measurement of ESs. The reasonable assessment of ESs can provide basic and important data for understanding the status of ESs in the YRD region. During the evaluation process, however, subjective bias was introduced because some parameters of the ES models were calculated by following relevant studies. The InVEST model ignores the regional characteristics of geographical elements and assigns the same value to the same land type, resulting in a deviation between the results of the evaluation and reality. Therefore, future studies should improve and verify the parameters. Second, the TSD indicator was developed and applied to analyze the trade-offs/synergies among ESs in the YRD region and effectively quantify the complex relationships that exist between ESs. However, a temporal scale was not included in this study. Some scholars have pointed out that the relationship between ESs varies temporally (Wu et al. 2019; Braun et al. 2018). In addition, the reliability of the results regarding the trade-offs/synergies can be improved by using long-term time series data. Therefore, future studies need to identify the relationships between ESs using long-term series data to mitigate uncertainty about the trade-offs/synergies that exist among ESs and analyze the impacts at the temporal scale. Third, limitations exist in terms of the analysis of the influence mechanisms of the trade-offs/synergies among ESs. This study investigated the effects of natural and socioeconomic factors on the trade-off/synergy relationships among ESs by considering six factors (ELE, PRE, TEM, GDP, POP, BUL). The findings suggest that these factors have significant effects on ES relationships. However, the complex relationships between ESs may be affected by other factors (e.g., soil properties, slope, solar radiation) (Sun et al. 2020; Schirpke et al. 2019). It is of great importance to consider more potential factors to improve the understanding of the influence mechanisms of the trade-offs/synergies that exist among ESs.

5. Conclusions

The results of the trade-off/synergy analysis enables decision makers to develop effective regional planning and ecological management policies that promote sustainable development. In this study, we investigated spatiotemporal changes in three ESs, namely, CS, WP, and BC, in the YRD region from 2005 to 2015. The results revealed that CS, WP, and HQ decreased by 1.17%, 2.49%, and 3.38%, respectively. These variations in three key ESs in the YRD region imply that ESs have degraded mainly due to intensive human disturbance in recent years. In addition to measuring the trade-off/synergy relationships between multiple ESs, this study measure their magnitude using an innovative indicator (TSD). The TSD indicator was proven to be efficient for identifying the types of relationships that exist between ESs and quantifying the intensity of the trade-offs/synergies. The relationships between the factors and trade-offs/synergies were revealed by using MLR and GWR models. This study demonstrated that the trade-off/synergy relationships presented significant autocorrelations. The GWR model performed better than the MLR model in explaining variations in the trade-off/synergy intensity, as the GWR model generated higher R^2 values and lower AIC values. The impacts of natural and socioeconomic factors on the trade-offs/synergies were spatially heterogeneous rather than spatially consistent. Our findings show that the GWR model can be used to obtain precise information on the various roles of the related factors at different sites in the study area rather than producing a global coefficient for the entire area. The trade-off/synergy intensity is significantly correlated with meteorological, urbanization, and terrain factors. The findings improve the understanding of the trade-off/synergy relationships that exist among ESs and their influencing mechanisms. The trade-off/synergy relationships among ESs in the YRD region are not only affected by environmental factors but also significantly related to socioeconomic development. Furthermore, the spatial heterogeneity of the trade-offs/synergies is well explained by the influencing factors. The GWR model revealed that these relationships are spatially heterogeneous rather

663 than spatially consistent relationships.

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669 **References**

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846

Figures

Figure 1

The YRD Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Land cover map of the YRD region in 2005 and 2015. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Spatial patterns of ESs in the YRD region at the grid scale (CS: carbon storage; CP: crop production; WP: water purification; BC: biodiversity conservation). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Spatial patterns of ES variations at the county scale in the YRD region (CS: carbon storage; CP: crop production; WP: water purification; BC: biodiversity conservation). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Spatial patterns of the synergies and trade-offs (measured by TSD) among multiple ESs at the county scale in the YRD region (CS: carbon storage; CP: crop production; WP: water purification; BC: biodiversity conservation). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

Coefficients of the relationship between the TSD of paired ESs and six variables using the GWR model.

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