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Trade-offs and synergies of ecosystem services in the Yangtze River Delta, China：response to urbanizing variation

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Abstract

Since entering the ‘Millennium of the cities’ omnipresent rapid urbanization has caused dramatic changes to ecosystem functions and generated huge ecological risks across city catchments. An understanding of how multiple ecosystem services are associated across complex social-ecological systems is required for urban sustainability. However, few studies have explored how the trade-offs and synergies of ecosystem service response to the traits of urbanization processes such as the variation of undeveloped-developed continuum. In this study, we took the Yangtze River Delta in China, a typical megapolis, as the case study area and quantified seven ecosystem services at a 10km x 10km spatial scale. We presented the spatial distribution and interactions of these services and identified whether they coexist in the form of specific cluster types. We found positive spatial autocorrelations across the study site. A significant tendency of trade-offs was detected between regulating and agricultural provisioning services, and we also spotted the possibility of both trade-offs and synergies that regulating and (different) cultural services were able to provide. Our results identified four different cluster types, and the cluster distributions are strongly associated with the urbanization levels - a tendency for urbanizing areas to witness the function shift in the certain order of ‘ecology – provision – multifunction – accessibility’. This provides a deeper understanding of the interactions among multiple ecosystem services and how they were determined by the ongoing social-ecological influences. The close connection between urbanization processes and ecosystems interact across developing and developed areas should be taken into consideration for future landscape planning.

Keywords natural capital • city planning • landscape management • spatial pattern • urbanization • YRD

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1 Introduction

Ecosystems are the foundation of human society and benefits their well-being and livelihoods through simultaneously generating multiple services including provisioning, regulating, supporting and cultural services (Costanza et al. 1997; MEA, 2005). Ecosystem services (ES) management has been commonly utilized in sustainability science and the number of publications has strongly increased in the past few decades (Costanza et al. 2014; Fisher et al. 2009). The usage and availability of ESs are influenced by the inextricable social-ecological linkages emerging with the surrounding landscape. For example, the ecosystem structure and function can be changed by human-driven forces including urbanization, agriculture, and associated irrigation and deforestation (Willemen et al. 2010; Zank et al. 2016). Different uses of landscapes determine the diverse feedbacks and interactions among different ecosystem services, i.e. so-called spatial trade-offs or synergies, which express how the provisioning of one service interacts or inhibits the delivery of another service, or how multiple services exhibit spatial concurrence in the certain area (Carpenter et al. 2009; Rodriguez et al.2006). Knowledge of the interactions and feedback among different ecosystem services determines the pivotal application of the ES concept into practical decision-making in the field of evaluating whether it is sustainable, worthwhile or resource/cost-efficient to enhance the provision of one ES with possibly posing supporting or impairing effect to another ES （Haase et al. 2012; Mouchet et al. 2014; Armatas et al. 2018）. For enhancing multi-functionality and avoid the proliferation of disservices, a better understanding of spatial pattern of multiple ES and their interactions, especially synergies and trade-offs is absolutely necessary (Cavender-Bares et al. 2015; Howe et al. 2014). However, there is still limited understanding of how multiple ecosystem services are associated across complex social-ecological systems and how they interact with different social and biophysical conditions (Bennett et al. 2015). And this is particularly important in rapidly urbanized areas where the human well-being mainly depends on services provided by semi-natural or artificial ecosystem (Rall et al. 2017; Yang et al. 2015), but most previous studies have focused on less disturbed ecosystems and concerned with services that generated by natural capital even when studying the urban ecosystems (Dolley et al. 2020). More attention, definitions and interpretation for human-dominated ecosystem its services are needed (Hansen and Pauleit 2014; Ramyar 2019).

Urbanization is a major driver of global environmental change and it can no longer be neglected in the construction of sound ecological science (Elmqvist et al. 2013). With the continuous increase in global population and economics, the expansion of urban area is omnipresent (Haas and Ban, 2014) and have considerable impacts on natural resources, functions of ecosystems and biodiversity, resulting in ecological crisis such as freshwater scarcity, air pollution, regional climate change (Chu et al. 2016). Most evidence indicates that anthropogenic activities have detrimental impacts on ecosystem services except that the growth of population and residential area can promote the supply of agricultural production service (Li and Zhou, 2016; Su et al. 2014). However, given that the pattern of urban development is ever-changing and tend to show spatial heterogeneity, it deserves more efforts to clarify the spatial patterns of ecosystem services in and around cities (Marshall and Dolley 2019; Peng et al. 2017). Some studies have analyzed the ES supply along with urban-rural gradients which is usually related to the landscape change (Balzan et al. 2018; Kim et al. 2020), but how the trade-offs and synergies of ecosystem service are associated with the complex traits of urbanization (e.g., population, economic and land conversion) remains unclear. Currently, and likely to be increasingly important in the next decades, landscapes will be dominated and intensively managed in the face of strong agricultural and urbanization pressure (Haas and Ban, 2014; Xie et al. 2015). Hence, it is crucial to derive a full understanding of trade-offs and synergies among multiple ecosystem services in such human-dominated landscapes, especially how these are manifested across the landscape as part of the urbanization process and the wider influence of this.

To meet the growing demand for effective ecosystem-based management, approaches have emerged for revealing the linked nature of ecosystem services, identifying the prioritization of key conservation areas and informing land-use planning or decision making (Barral and Oscar 2012; Queiroz et al. 2015; Galler et al. 2016). Theoretical frameworks (Bennett et al. 2009; Fisher et al. 2008), quantitative indices system (Willemen et al. 2010), valuation models (Nelson et al. 2009) and integrated modeling tools (Villa et al. 2014; Zank et al. 2016) are applied to explore the relationships among multiple ecosystem services. Using the concept of spatial bundles referring to “sets of ESs that repeatedly appear together across space or time’(Carpenter et al. 2009; Raudsepp-Hearne et al. 2010) ,empirical studies were conducted to detect trade-offs and synergies among ES while linking the relationships with social-ecological conditions (Baró et al. 2016;Spake et al. 2017). This established methodology often consists of individual ES pattern, paired correlation, principle component analysis (PCA) and cluster identification (Turner et al. 2014; Schirpke et al. 2019), but it remains unclear how the bundle distribution are determined by social and ecological factors especially the linkage in between the ES tradeoffs, synergies and urbanization attributes, and whether the distinct characteristics of bundle distribution can be detected at a larger scale like city agglomeration needs further exploration. Understand how the constantly evolving influence of urbanization on ES dynamics will make it possible to formula sustainable measures and policy interventions for navigating the tradeoffs that arise among different ecosystem services.

In this study, we address the aforementioned issue for the Yangtze River Delta (YRD), one of the most densely populated coastal areas in China. China has been undergoing rapid urban growth since the implementation of reform and opening policy in the late 20th century, with an average annual expansion rate of 8.74% from 1992 to 2012, a sharp contrast with the global average of 3.20% (He et al. 2014). Urban expansion has caused a massive loss of fertile agricultural land and increasingly threatened natural habitat and ecologically sensitive areas in China (Cao et al. 2017; McLaren, 2011). The YRD has been one of the most developed areas in China and it is characterized by massive rural-urban migrations, the expansion of urban areas and threatened regional eco-safety. Previous studies on the ecosystem service of the YRD have been focused on the identifying the economic values or spatial pattern of single ecosystem items (Cai et al. 2017; Wang et al. 2008), while the interactions between multiple ecosystem services remains an area to be investigated. Therefore, we focus on seven ecosystem services and their internal relationship in the context of urbanization. Our specific study aims were: (1) to reveal the distinct spatial pattern (if any) of ecosystem services across the YRD, (2) to assess if the ecosystem services coexist with specific clustering characteristics and (3) to understand the linkage between urbanization and ecosystem service trade-offs or synergies.

2 Methods

2.1 Study site

The Yangtze River Delta (YRD) region, which covers an area of approximately 210700 km^2 (115.7°E to 122.2°E and 28.8°N to 33.4°N), is located in the coastal region of Eastern China (Fig. 1). According to the '*Yangtze River Delta Region Metropolitan Development Vision Plan'* released in 2016, it encompasses one municipality (Shanghai) and twenty-five prefecture-level cities in three provinces (Jiangsu, Zhejiang and Anhui). By the end of 2030, the YRD is expected to be one of the sixth largest megalopolis areas in the world, with vibrant and diverse economy, leading to innovation and wide international influence. Owning to the advantages and foundation of prominent geographical conditions, strong comprehensive economic strength and complete urban system (Chen et al. 2019), the YRD comprises 2.2% of the country's landmass with 150 million inhabitants (11% of the country's population) and contributes 18.5% of the nation's Gross Domestic Product (GDP). The level of urbanization of the YRD has reached 68.2% in 2015, which is significantly higher than the national average (56.1%) (NBSC, 2016).

The YRD is the largest estuarine delta alluvial plain in China. It is influenced by the subtropical monsoon climate, with average temperatures ranging from 5.5°C in winter and 28.1°C in summer, and average yearly rainfall of 1,100 mm (NBSC, 2016). Due to the warm and humid climate with abundant precipitation, the well-irrigated plain produces abundant grain, cotton and tea, making the agricultural sector an important part of the economy (Wang et al. 2012). Forest clearance and human disturbances have severely changed the originally most forested (conifer and deciduous broadleaved trees) landscape since the early civilizations (Yi et al. 2003). Forests now cover approximately 27.4%, while agriculture occupies 49.7% of the total YRD area (NBSC, 2016). In the past few decades, urban land use has rapidly expanded and impacted many ecosystem services, generating serious ecological crisis such as a broad decline in the density of river network, loss of fertile soil and climate change (Han et al. 2015; Yi et al. 2003). Furthermore, there are great variations in different regions with respect to urbanization level and urban growth rate, while some cities have extremely high population density (like Shanghai, Nanjing, Wuxi), others have quite a low population density (some cities in Anhui Province). Meanwhile, many primarily rural towns are developing into cities and are experiencing massive demographic and economic transitions, which could fundamentally change the landscape pattern and ecological function. Therefore, this case-based study is important enough to generate a comprehensive outlook on the delivery and interaction between multiple ecosystem services across the southern watershed of the China where urbanization, population and economic growth has been the most dramatic.

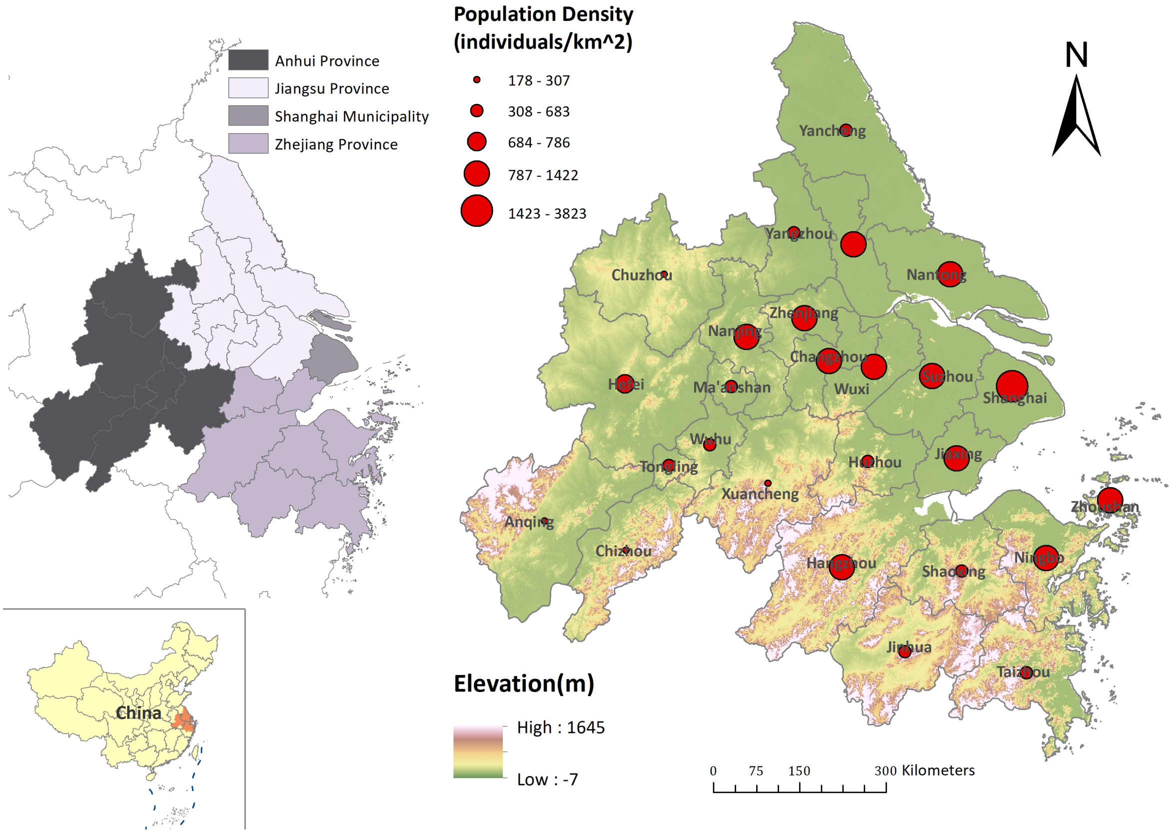

Fig. 1 The Yangtze River Delta (YRD). Population density (red circles) and elevation (color gradient) within the cities of the YRD

2.2 Integrative analytical framework

To examine the spatial pattern of multiple ecosystem services and their relationship dynamics with urbanization, we designed an integrative analytical framework (Fig.2). The rapid urbanization process goes along with growth of populations, economics and dramatic land use transitions, leading to profound influence on local socio-ecosystem and landscape functions. Those change often involves biochemical properties and ecological mechanisms (the interactions among the atmosphere, hydrosphere and biosphere) that underpin ecosystem services, and consequently result in heterogeneity of ES spatial distribution, bundle pattern, tradeoffs and synergies. In order to increase human well-being while maintaining the natural system and process, this current study explores the dynamic change and feedback influences about ES trade-offs and synergies response to the traits of urbanization process, which can be used for environmental management or nature-based solutions.

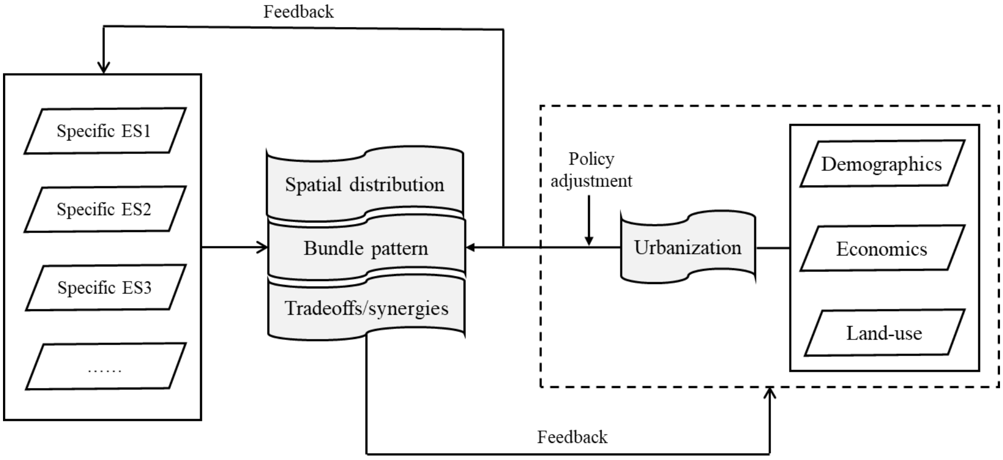

Fig.2 Integrative analytical framework of ecosystem services trade-offs related with urbanization

The range of different ecosystem types combined with a complex physiographic setting generates multiple ecosystem services for human society in the YRD region. The economically developed metropolitan areas are facing major environmental challenges such as high population density, insufficient per capita green spaces, serious air pollution and wetland loss (Cai et al. 2017). Considering these issues, ecosystem services were selected for this study based on their importance in urban ecosystems and their relevance to indigenous well-being. Therefore, seven typical ecosystem services were distinguished and evaluated. These services could reflect the local context of the study area, covering the first, second and tertiary sectors and economy. The indicators for the seven ecosystem services and required data were shown in Table 1. Details of the quantifying for the indicators were provided in Section A of Supplementary material.

Referring to the previous studies (Kienast et al. 2012; Turner et al. 2014) and based on the different input data, we applied a 10km x 10km fishnet to create a uniform grid covering the study region. We believe that this was the most parsimonious trade-off between accuracy and uncertainty in the data and ensured we did not over-interpolate, but maintained spatial differentiation and ran the analysis at a scale that could be useful for the planning process.

Table 1 Calculation methods and data sources for quantifying ecosystem services

Ecosystem service	Indicators	Data collection
CROPS	Annual crop yield	Crop yield data ^{a}, cultivated land quality data ^{b}.
CARBON	Net primary productivity	NDVI data ^{c}, Meteorological datasets including solar radiation, precipitation and temperature ^{d}.
WAT_ST	Runoff depth.	Precipitation, soil type and soil texture map ^{b}, Vegetation cover map ^{e}.
AIR_REG	PM2.5 removal	NDVI data ^{c}, atmospheric $PM_{2.5}$ concentration ^{f}

HABITAT	Biological migration resistance	LULC data in 2015[b]
TOURISM	Recreational opportunity spectrum	Traffic network [g], POI map [b]
PLACE_SEN	Protected areas	The List of Nature Reserve [h]

[a] Crop yield survey; [b] Data Center for China Resources and Environmental Sciences (http://www.resdc.cn/); [c] Downloaded from LAADS DAAC (https://ladsweb.modaps.eosdis.nasa.gov/);[d] China National Meteorological Science Data Center (https://data.cma.cn/); [e] GLC2000 dataset; [f] Environmental Status Bulletin of each county; [g] National Geographic Data Center (http://www.webmap.cn/).[h] Interactive map with geospatial data (http://www.gjgy.com/)

2.3 Quantification of ecosystem services

(1) Crop production (CROPS): Food supply is pivotal for food security and sustainability of urban development. Here we used the annual crop yield as a proxy for the food supply service (Li et al. 2016). Generally higher crop yield is bound to higher quality cultivated land. Hence, a linear function was set to reveal the relationship between crop yield(kg/ha) and corresponding cultivated land quality (Haase et al. 2012). Then we estimated the crop production of each field-block and add up the total area of land under cultivation to 10-km squared grid cells.

(2) Carbon sequestration (CARBON): Forests are essential for above-ground carbon storage and combating the greenhouse effect (Nowak and Crane, 2002). Here, the amount of carbon sequestration was derived from the net primary productivity (NPP) according to the photosynthesis equation (Li and Zhou, 2016). The Carnegie Ames-Stanford Approach (CASA) model was performed to estimate the vegetation NPP in ENVI 5.3 platform (Sanchez-Azofeifa et al. 2016).

(3) Water storage (WAT_ST): The YRD is always regarded as the water tower for the territory of eastern China and the evaluation of water retention capacity is crucial for ecosystem function assessment (Jia et al. 2014). The approach of comprehensive water yield capacity based on vegetation fraction including canopy, understory layer and soil, has been widely adopted in southern China (Du et al. 2019) and our study adopted this method. The water storage of each vegetation fraction was calculated using a set of data including vegetation cover, regional precipitation, soil type and soil texture data (related to the water holding capacity of soil) (Sun et al. 2017).

(4) Air quality regulating (AIR_REG): Air quality is critical for urban residents and vegetation improves air quality via removing

pollutants from the atmosphere (such as NO_x, O_3, CO and particulate) (Akbari et al. 2001). Here, we adopted the removal of a key pollutant (i.e. $PM_{2.5}$, the particulate with the diameter fewer than 2.5μm) as a proxy for air quality regulating service. The arguments on particulate removal were acquired from (Jim and Chen, 2008).

(5) Habitat suitability (HABITAT): Habitat adaptation plays a significant role in the organism flow among habitat patches and thus, supports biodiversity conservation (Zeller et al. 2012). The biological connectivity model was well used to estimate animal migration resistance which can to some extent represent habitat suitability. We use the least-cost approach in ArcGIS for measuring the cost to move between habitat patches based on detailed geographical information about the landscape. Longer cost distances illustrate that organisms need to overcome greater resistance to reach landscape patches, and therefore represent poor habitat suitability (Adriaensen et al. 2003; Zeller et al. 2012). The highest computed values represented the poorest habitat suitability and hence we used reversed normalization([maximum-value]/[maximum-minimum]) to derive the final results.

(6) Recreational ecotourism (TOURISM): Recreation opportunities provided by natural and semi-natural landscapes is a major content of human benefits and has emerged as the linkage between ecosystems and society (Recasens et al. 2016). Here, we aggregated the amount of nature recreation facilities according to the POI (point of interest) spatial statistic. This dataset does not cover artificial attractions or amusement parks, but only nature-related recreational facilities including (scenic viewpoints, tourist attractions, observation towers and associated amenities). For each grid cell, we summed the points, the access paths and the area of the natural recreation facilities and standardized the sums using the zero-mean normalization approach. This method for quantifying cultural service was also used in Bieling and Plieninger (2013) and Turner et al. (2014).

(7) Sense of place (PLA_SEN): Sense of place usually refers to a particular feeling or perception held by people which often make a place unique or special. In our study, this was evaluated by the major conservation sites in each grid cell. We included areas listed in the Natural Conservation Scheme, most of which are aimed at the conservation of natural(biotic) resources and cultural heritage sites. We mapped each site with its location, area, path lengths and the popularity weighting factor (i.e. a 3-level weighting factor (1-0.7-0.5) corresponding to the criticality class (national- provincial-ordinary) (Wu et al. 2015). Then the area and path lengths were reclassified into values between 1 to 10 and we multiplied the reclassified value of the area, path length

and the weighting factor. Finally, the results of the points were summed to each grid cell thus derive the service value of the entire study area.

Due to the different data sources and sampling methods, CROPS, CARBON, WAT_ST, AIR_REG and HABITAT was calculated at 1 km x 1 km grid and transformed to the mean value in 10 km x 10 km grid cell. Afterward, we performed log-transformation on CROPS, CARBON, WAT_ST, AIR_REG to transform the data to normality for the ensuing correlation analysis.

2.4 Analysis

2.4.1 Spatial patterns

The process of individual ecosystem service measure was realized in ArcGIS 10.2. Moran' *I* index was applied to quantify the spatial clustering of all the ecosystem services in GeoDa software.

2.4.2 Cluster of ES trade-off patterns

Pearson's correlation was applied to evaluate the pairwise relations between ecosystem service measures. Then we performed Principal Component Analysis (PCA) to reduce the dimensionality of the datasets and quantify the main multivariate interrelationships between different service variables. According to the Guttman-Kaiser criterion (eigenvalue>1), we recognized three components that were adequate to describe the structure of the data. Based on this, the *K*-means clustering analysis was used to group the grid cells to distinct types and radar diagrams used to visualize these cluster types. This method has been widely used to categorize areas with similar sets of ecosystem services (Chawanji et al. 2018).

2.4.3 ES trade-offs and synergies response to urbanization level

Urbanization is always manifested in economic development, population growth, expansion of construction land and improvements of people's livelihood (Jiang and Lin, 2012). They form the foundation, provide further impetus and also become major embodiments for urbanization. In this study, we selected three indexes to reflect three aspects of urbanizing variation (population, economy and land), i.e., population density, GDP density and the proportion of construction land, respectively. We collect population and GDP data at a spatial resolution of 1 km x 1km, supplied by Global Change Research Data Publishing and Repository (http://www.geodoi.ac.cn/). The construction land distribution was extracted from the LULC map. All data were aggregated to the total value of 10km x 10km grid cell. We computed the proportion of construction land in each grid cell to give a more clarified indicator. Similarly, the population and GDP data were log-transformed, construction land proportion was ln-transformed to give a more uniform distribution.

We use the Kruskal-Wallis test to test whether significant differences in urbanization level existed across different cluster types. Then we use the density plot to visualize the distribution of the numerical index of urbanization level of different ES trade-offs type. To furtherly explore how ecosystem service trade-offs varied with urbanization, we displayed the scatter plot matrix of paired ecosystem trade-off degrees with varying urbanization levels. We first standardized the individual ecosystem service via ([maximum-value]/[maximum-minimum]). Referring to the root mean squared deviation (RMSD) which approximates the average deviation from the mean benefit (Bradford and D'Amato, 2012), we calculated distance between the point (S_{E1}, S_{E2}) and 1:1 line (i.e. $D = \sqrt{([(S_{E1} - S_{E2})]^2/2)}$) as a proxy for the trade-off degree between pairwise ecosystem services.

3 Results

3.1 Spatial patterns

Each service was presented using distinguished color coding that corresponds to the reclassified value (Fig. 3). CROPS was most strongly represented in the northern and northwestern YRD where the main land use type is the cultivated land (paddy field and upland field), while CARBON, WAT_ST and HABITAT were most plentiful in the densely forested southern region. AIR_REG had the highest concentration in the southwestern area and relatively high values in some peri-urban regions such as western Shanghai, middle Jiangsu and Northern Anhui. The cultural services TOURISM and PLA_SEN were concentrated in areas famous for high recreational opportunities like Shanghai, Tai Lake district in Suzhou, Nanjing, West Lake and Thousand-Island Lake in Hangzhou. The southern Anhui with high SEN_PLACE value, however, was less competitive in TOURISM.

All the ecosystem services displayed strong spatial clustering with significant positive spatial autocorrelation (Fig. 4 and Section B of Supplementary material). We checked the Moran's *I* index at different distance levels and there existed a significant positive agglomeration effect within the distance range of 150 km (Moran's $I > 0.1$). HABITAT showed the strongest coherence while WAT_ST and AIR_REG displayed the weakest spatial dependence and turned to a random dispersion at distance of approximately 150 km.

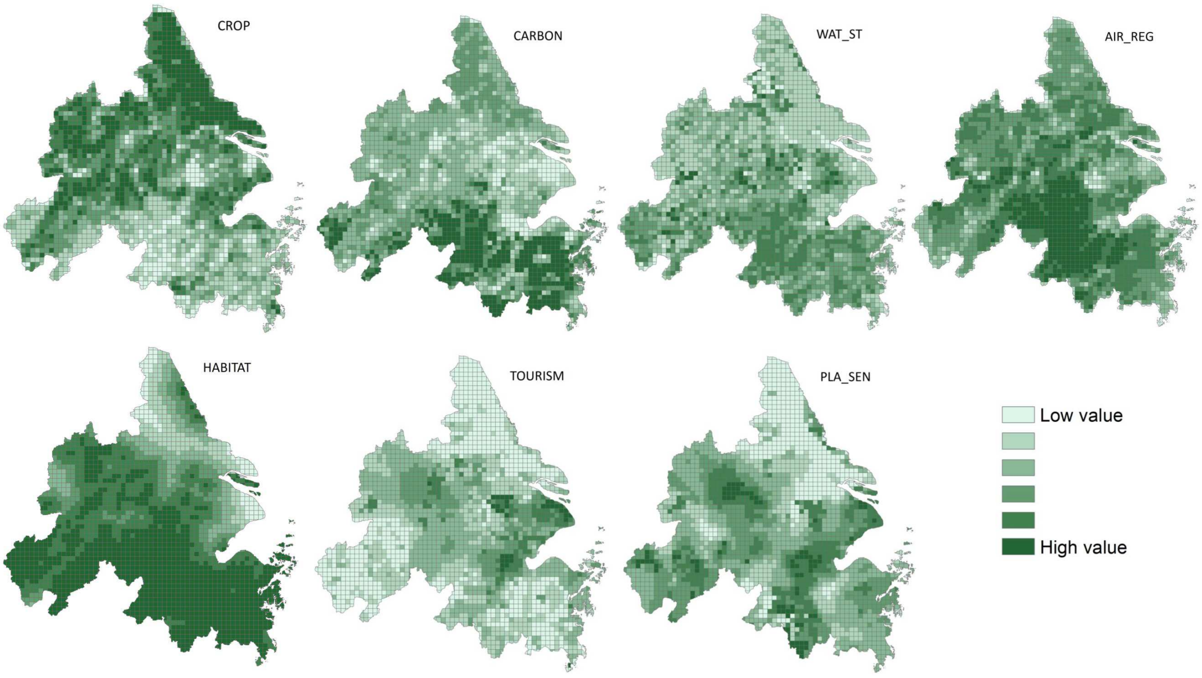

Fig. 3 The spatial distribution of each ecosystem service, with distinguished color coding corresponding to the reclassified value by natural breaks method

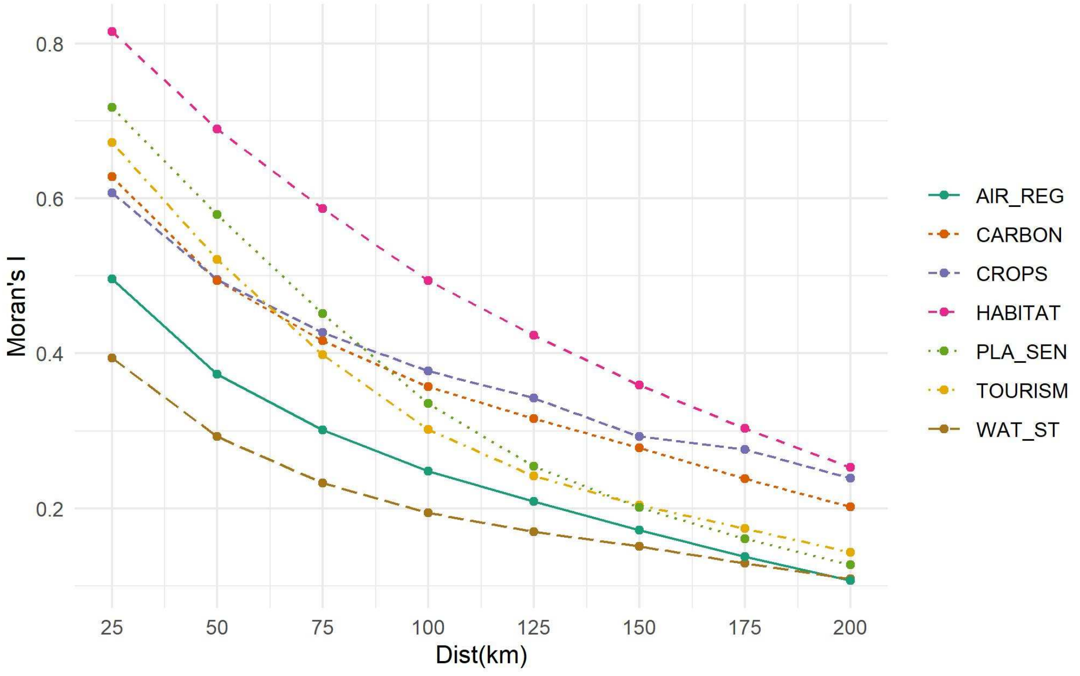

Fig. 4 Moran's *I* spatial autocorrelation of seven ecosystem services as a function of the distance

3.2 Cluster of ES trade-off patterns

We found 18 significant (11 positive and 7 negative) interactions among ecosystem services measured (see Table 2), with the strongest correlation between TOURISM and PLA_SEN (positive), and CROPS and CARBON (negative). CROPS was negatively correlated with other ecosystem services, except for the weak positive correlation with AIR_REG. Regulating service had positive correlations with PLA_SEN but negative correlations with TOURISM.

Table 2 Pearson's correlation analysis with coefficients in the top right half and the significance level in the low left half. High correlation (dark red or dark blue)>0.3; weak correlation (light blue or light red)0.1-0.3; no correlation(white)0-0.1

CROPS	-0.394	-0.152	0.291	-0.412	-0.183	-0.252
<.001	**CARBON**	0.175	0.362	0.33	-0.166	0.264
0.009	0.003	**WAT_ST**	0.278	0.154	0.072	0.061
0.002	<.001	<.001	**AIR_REG**	0.225	-0.015	0.148
<.001	<.001	0.004	<.001	**HABITAT**	-0.212	0.347
0.004	0.014	0.862	0.581	<.001	**TOURISM**	0.519
0.002	0.001	0.023	0.016	<.001	<.001	**PLA_SEN**

PCA was then applied for the analysis for characterizing the trade-off patterns of ecosystem services. We concluded the first three components that accounted for 75.3% of the total variation (Table 3 and Fig. 5). The first component explained 33.7% of the variance and showed a trade-off between the food provision on the one side, while regulating and cultural service on the other, which appears to separate the landscapes dominated by agricultural production from the others specialized in regulating and cultural service. The second principal component explained 22.5% of the variation in the dataset and mostly described gradients in TOURISM and PLA_SEN. The third component accounted for 19.1% of the variation and mostly described ingredients in CARBON, WAT_ST and AIR_REG which are related to ecological integrity.

Table 3 Principle component loadings. The listed information showed how the identified PC (eigenvalue>1) was interpreted by each ES

	PC.1	**PC.2**	**PC.3**
CROPS	0.647	-0.012	-0.024
CARBON	-0.299	-0.197	0.530
WAT_ST	-0.208	0.177	0.440
AIR_REG	-0.161	-0.327	0.342
HABITAT	-0.467	-0.095	0.191
TOURISM	-0.429	0.447	0.276
PLACE_SEN	-0.531	0.419	0.237
Eigenvalue	1.536	1.255	1.124
Proportion	0.337	0.225	0.191
Acum.prop	0.337	0.562	0.753

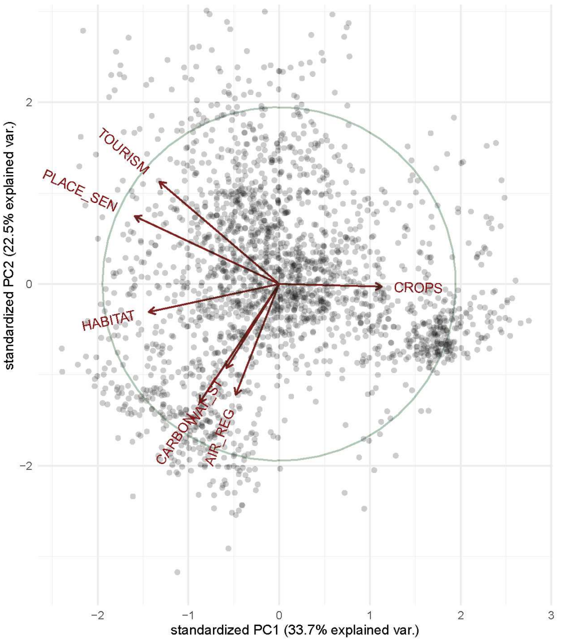

Fig. 5 Principal component biplot illustrating trade-offs and synergies among seven ES

The cluster results of K-means algorithm allowed us to delineate the ecosystem service grouping. The optimal number of clusters was four according to curve of the total within sum of square (Section B in Supplementary material). Fig. 6 revealed the distribution of each clustering type with the radar diagram determining the average value of each ecosystem services in different clusters. The first cluster mainly distributed in the northern region of YRD was dominated by crop production service; the second cluster distributed in the central large cities and as well as southwestern part, was dominated by two services, Tourism and PLA_SEN and the medium values of WAT_ST. The third cluster was a multiple-use d type with medium values of all services. Cluster four, mostly lied in the southwestern area was dominated by WAT_ST and CARBON as well as medium value of HABITAT and AIR_REG. Based on the interpretation of the characteristics of the clustering types, we adopted the following names for cluster (1)-(4): cluster (1): Provision-related trade-offs; type (PRT); cluster (2): Accessibility related trade-offs (ART); cluster (3): Multifunctionality-related trade-offs (MRT); cluster (4): Ecology-related trade-offs (ERT). In terms of the areal extent, MRT cluster and ERT cluster were the most widespread in the study area whereas ART had the lowest spatial coverage.

3.3 ES trade-off response to urbanization level

According to the Kruskal-Wallis test, significant differences in urbanization level were observed among different ecosystem service trade-off clusters, showing by p-value<0.0001(Table 4). The density plot was used to simply and effectively stress the difference of population density, GDP density and construction land proportion in different ES trade-offs cluster (Fig. 7).

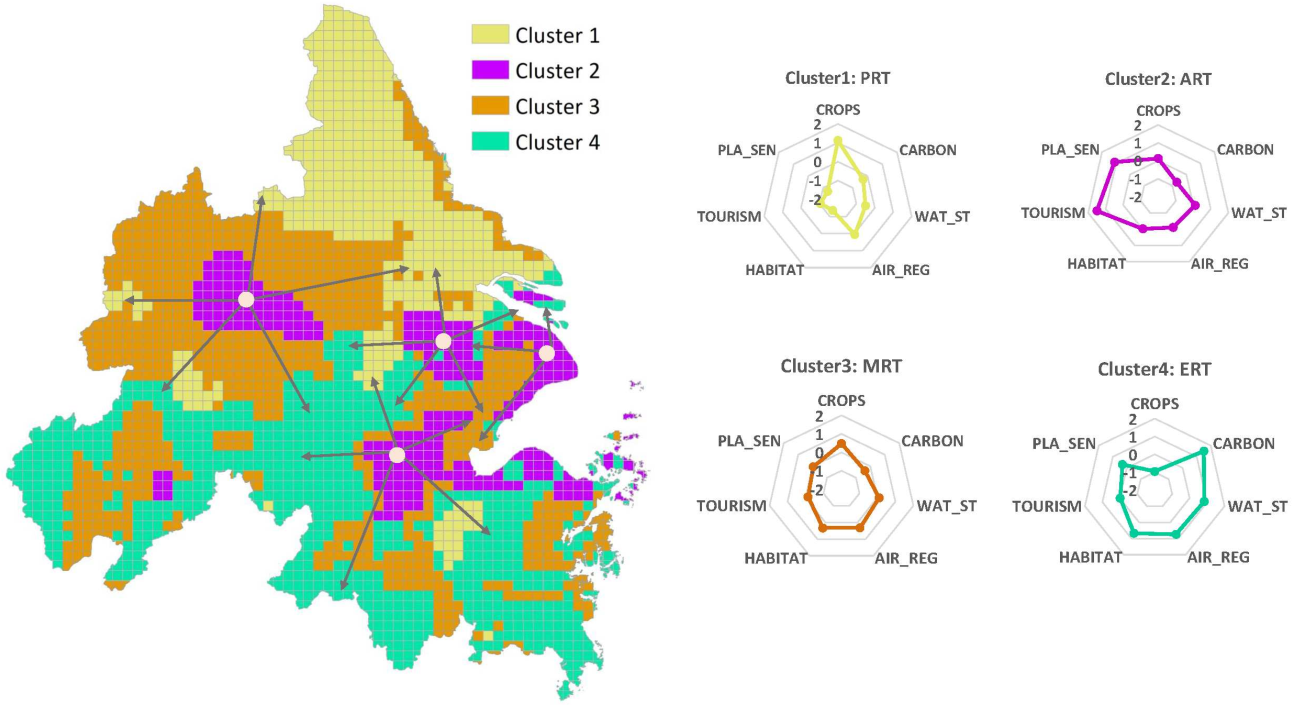

Fig. 6 Clustering type of ecosystem service trade-offs and radar diagram of ecosystem service average value in each cluster (PRT: provision-related trade-offs; type; ART: accessibility related trade-offs; MRT: multifunctionality-related trade-offs; ERT: ecology-related trade-offs)

Table 4 The result of Kruskal - Wallis test to identify the difference of urbanization level among different ES trade-off clustering types.

Variables	Chi-squared	df	p-value
lg (Population density) ~ cluster type	215.64	3	<0.0001
lg (GDP density) ~ cluster type	340.72	3	<0.0001
ln (Construction land proportion) ~ cluster type	422.86	3	<0.0001

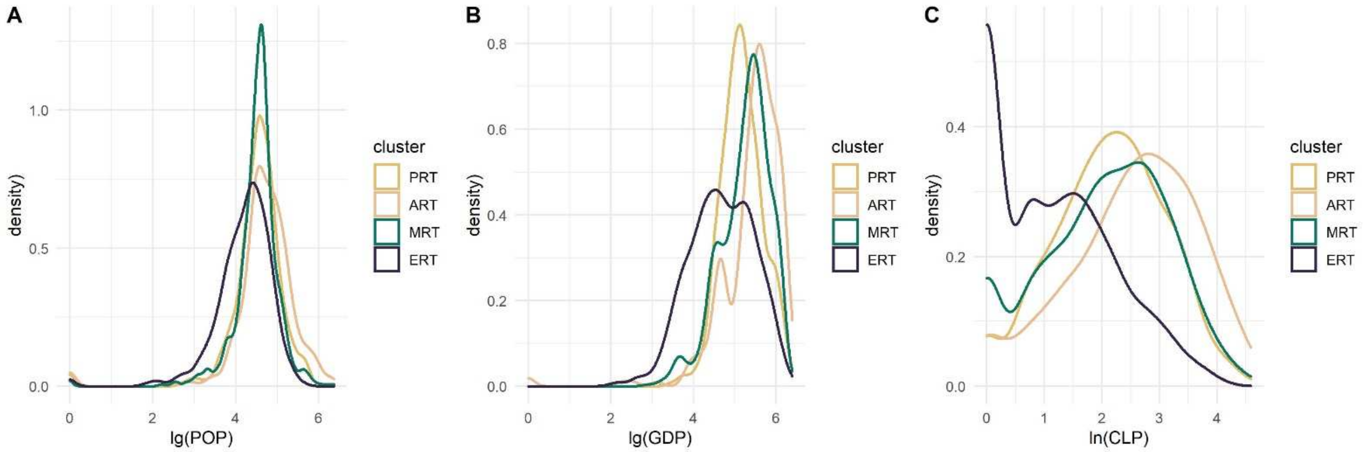

Fig. 7 Urbanization variation of each ES trade-off cluster (PRT: provision-related trade-offs; ART: accessibility related trade-offs; MRT: multifunctionality-related trade-offs; ERT: ecology-related trade-offs). A: population density; B: GDP density; C: construction land proportion.

Overall, the ERT type corresponded to the lowest value of population density, GDP density and proportion of construction land, and this was interpreted as the limitation constraints on urban construction in areas with high ecological value or fragile natural environment. Although there are no significant differences in population density among different ES trade-off clusters, the ART cluster had the highest occurrence in most densely populated areas (the right end of the horizontal axis). In terms of the GDP of different clusters, the highest GDP tended to occur in ART zone, followed by the MRT and PRT zone. This may indicate that natural recreation facilities were beneficial to the human comfort of living space and they were positively related with economic development and enjoyable consumption. In addition, both MRT and ART clusters had a high occurrence in and around core cities, most of which are GDP-ranking top cities such as Shanghai, Hangzhou, Ningbo and Suzhou (NBSC, 2016). This showed that high-level urbanization areas were able to balance the various ecosystem services or improve the scenery quality and natural landscape accessibility. Also, ART cluster has the relative high construction land proportion, followed by MRT, PRT and ERT, hopefully suggesting the ecosystem function shift along with the gradient of land use conversion.

To further examine the interaction of ecosystem services trade-offs with urbanization, we used the scatter plot matrix to show the changes of paired ecosystem trade-off response to urbanization level (Fig. 8). Here we particularly focused on four paired ecosystem services with significant dynamic of trade-offs or synergies. As demonstrated in Fig. 8, the higher |D| value represented stronger trade-offs between paired ecosystem services. Higher CARBON with lower CROPS was most represented in the less urbanized area while developed areas tended to show relatively higher CROPS and lower CARBON. However, we noticed that the trade-off was ultimately mitigated in most developed areas. Such shifts were also detected in the trade-off between CROPS and WAT_ST. The dynamic nature of the trade-off between CARBON and AIR_REG showed higher lose-win situations (loss of CARBON and gain in AIR_REG) in developed urban areas. The trade-off degree between HABITAT and TOURISM was greatest in low-level urbanized areas and lowest in developed areas.

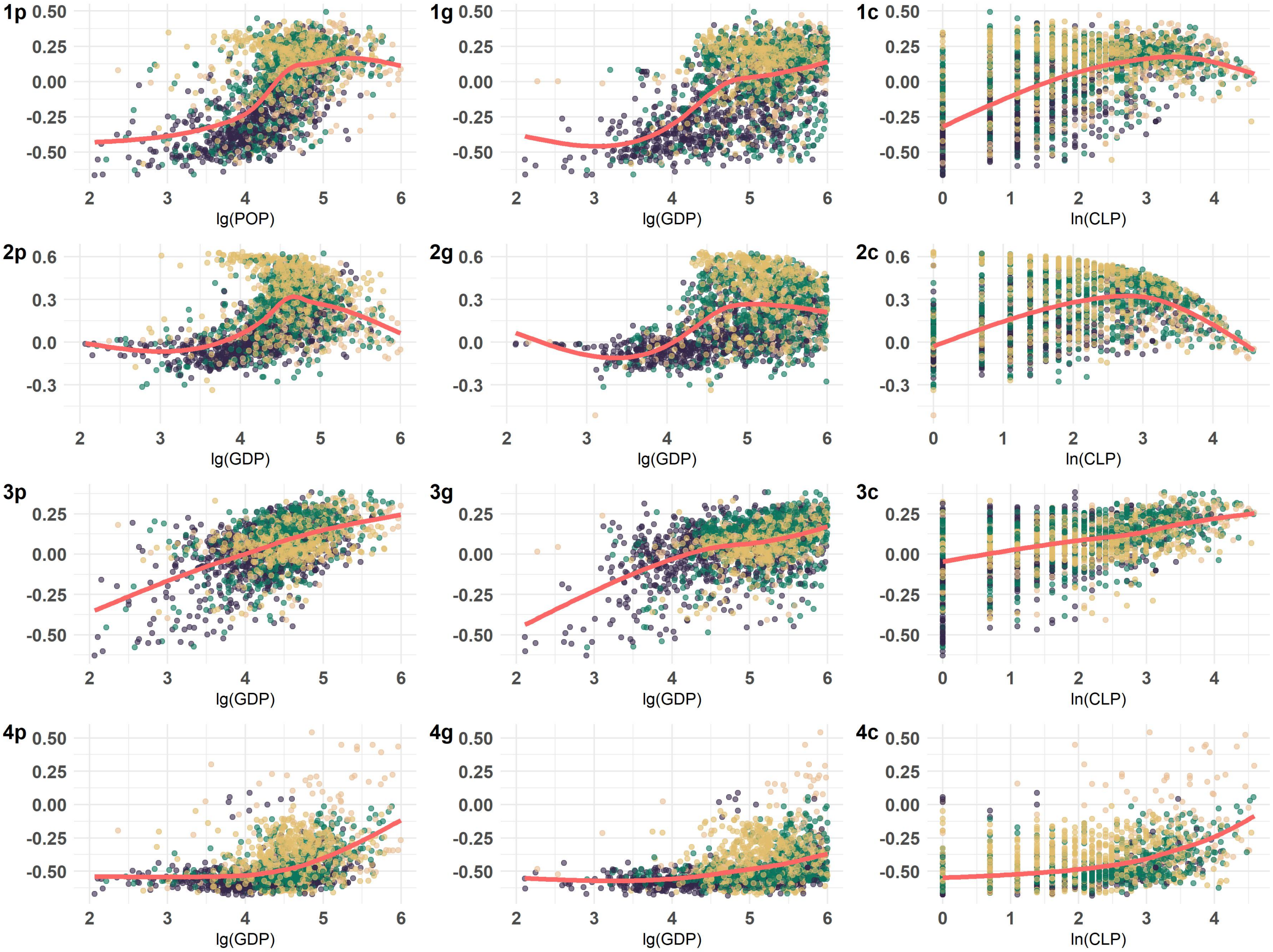

Fig. 8 Paired ES trade-off degree response to urbanization levels in the YRD. The former service is weaker than the latter service: horizontal axis value<0; The former service is stronger than the latter service: horizontal axis value>0. Distinguish point color represent the cluster type of each grid (PRT: provision-related trade-offs; ART: accessibility related trade-offs; MRT: multifunctionality-related trade-offs; ERT: ecology-related trade-offs).

4 Discussion

This study confirmed that the principle ecosystem services in the wider catchments of economically-developed metropolitan regions formed distinct clusters and they can be used to assess spatial trade-offs and synergies. As the work is focused on service delivery to people from the regulation carbon and water cycles, provision of clean air to access to places to enhance human well-being, much of the following discussion will be based on the grouping of trade-off clusters and how it interacted with urban development.

4.1 Spatial patterns of ecosystem services

Assessing and mapping the critical ecosystem services of the metropolitan areas is a first step for the deeper understanding surrounding the provision and delivery of multiple ecosystem services. Our results showed that the measured ecosystem services had distinct spatial heterogeneity and clustering characteristics (Fig. 3 and Fig. 4); these traits were also demonstrated in the ES quantification and mapping for Quebec (Canada) (Raudsepp-Hearne et al. 2010), Europe (Mouchet et al. 2017), Pearl River Delta (China) (Zhao et al. 2018). Such clustered or clumped distributions were mainly attributed to the aggregated geographical character. For example, the southwest mountainous and hilly area has the most various ESs and highest natural capital, while the northern lowland plain was dominated by agricultural development and habitat fragmentation caused by urban sprawl and growing residential area (Wu et al. 2017). Previous studies related with ES measurement in YRD have identified the spatial distribution of the multiple ecosystem services and demonstrated that regulating services (such as carbon sequestration, soil protection, water conservation and air regulation) were aggregately distributed in the southwestern mountainous areas while the hotspots of provisioning services (such as crops and livestock) were mainly in the northeastern parts (Cai et al. 2017; Yang et al. 2015). The distribution of estimated ecosystem services (CROPS, CARBONS, WAT_ST, HABITAT) in this study showed consistent spatial patterns compared with previous studies, demonstrating that the provision of individual ES is closely related to land use (Renard et al. 2015). The AIR_REG service, which had apparently the highest concentration in southwestern, also showed relatively high values in peri-urban regions (between remote areas and core cities). This can be explained by the industrial sector and consequently air pollutant emissions in those areas (Zheng et al. 2016). Recently some local governments have moved enterprises emitting the most industrial soot and dust from central city areas to less developed areas, leading to the higher air pollutants in peri-urban regions (Zhao et al. 2014). Such a case may also account for why CROPS (mostly located in the peri-urban area) has a moderate positive correlation with AIR_REG. What is more, our results differ from previous findings that the hotspots of cultural services widespread in the southwest mountainous areas. The cultural service TOURISM had the highest concentration in densely populated urban areas rather than the remoted southwest areas, albeit with superior natural values (densely forest-cover and high biodiversity). Those areas with relatively high PLA_SEN but limited TOURISM to some extent manifested the gap between the potential opportunities and actual delivery to the desired group.

4.2 Cluster types of ES trade-off

The relationships between multiple ecosystem services are often presented in trade-offs or synergies. Trade-offs can commonly be seen between provisioning service and other services, e.g., the increase of agricultural productivity in a fast-developing rural area often damages the avian habitat and also reduces species richness and carbon stock (Mastrangelo and Laterra, 2015). Empirical evidence has also provided that the positive interactions or the synergies within regulating services or between regulating service and cultural service (Galicia and Zarco-Arista, 2014; Zhao et al. 2018). According to the Pearson's correlation (Table 2), our study showed the trade-offs between the provisioning service and regulating services (CROPS and CARBON, WAT_ST, HABITAT), and synergies between regulating services (CARBONS, WAT_ST, AIR_REG). Such findings were similar to another YRD research from Cai et al. (2017) where the authors identified distinct spatial distribution of ESs hotspot such as ecological conservation zone and agriculture zone. This can offer great help for decision makers quickly identifying critical spatial spots and rationally decide priority conservation areas. The trade-offs between regulating and certain cultural service (TOURISM), which was also found in Pearl River Delta, another metropolitan region in southern China (Zhao et al. 2018). Case studies in Leipzig-Halle, Germany and Sweden also detected the hotspots of cultural services in urban densely populated areas and the lose-win patterns between recreation and ecological integrity or regulation services (Haase et al. 2012; Queiroz et al. 2015). Such evidence supported that the production of an ES is the combination of the social-ecological potential (management practices, biophysical conditions) and the human demand for the given service (Bagstad et al. 2016; Reyers et al. 2013).

The ecosystem services not only showed paired interactions but also displayed multivariate groups that defined the features of the ecosystem service co-production and trade-off. Earlier studies have used 'bundle' approach to characterize the various functions of landscape and connectedness or interdependence of multiple services (Bennett et al. 2009; Mouchet et al. 2017). For instance, bundle types were grouped including agriculture, forest and various mixed used in Britain and Barcelona (Baró et al. 2016; Dick et al. 2011), meanwhile, they were applied to group into plain, mountainous, island and mega-city in southeastern China (Yang et al.

2015). In this regard, the spatial cluster may well be a universal pattern in both regional and watershed-level organization of ecosystem services. There were strong signs of spatial trade-offs between provisioning service and other services, which was consistent with the previous empirical evidence that the north coastal area of Jiangsu Province having high agricultural land use pressure (Chuai et al. 2016). The ERT type, mainly distributed in the southwestern region, showed the most prominent regulating services was accompanied by high value of natural appreciation but relatively limited recreation service, reflecting the potential to enhance the societal benefits (Recasens et al. 2016). The ART cluster was often located in core cities and surrounded by MRT type in developing or peri-urban areas (Fig. 6), reflecting that ecosystem service clusters were relevant with geographical position or degree of centrality in the region (urban, peri-urban, rural). Peri-urban landscapes tended to be important areas for providing a diverse range of ecosystem services (Turner et al. 2014). Besides, the small area of MRT scattered along the north coastal Jiangsu, which had high value of natural assets especially prominent biodiversity (Cui et al. 2016). We suggested that sustainable management of this area with strong wetland conservation and restoration is critical for the nation’s coasts that are facing increasing human pressure.

4.3 ES trade-off associated with urbanization level

There seemed a tendency for urbanizing areas to witness the function shift in the certain order of ERT – PRT – MRT – ART (Fig. 6 and Fig. 7). Reviewing the historical dynamic of urban development and landscape change in YRD would help illustrate such a shift. Due to the rapid urbanization since the 1980s, large amounts of immigrants from other parts of China moved to the first large urban agglomeration including Shanghai, Nanjing, Suzhou, Wuxi, Changzhou, Hangzhou and Ningbo (Luo et al. 2018). Hence, large parts of the northern plain have been developed into rural settlements and cultivated land to satisfy the huge grain demands from the large and rapidly growing population (Zhang et al. 2013). Due to the inconsistent pace of economic advancement, Shanghai has become the most populous urban area and a center for finance, innovation and transportation in China. The booming economy in Shanghai has positively driven the development of Suzhou, Hangzhou and Nanjing, which have also grown to big cities (Lin et al. 2017). However, the southwestern part did not catch the pace of the development of the northeastern part, leading to the quite slower expansion of urban expansion than the northwestern part (Luo et al. 2018). Yet the southwestern areas play an important role in ecological integrity including forest conservation, air quality and water resources protection.

The trade-off degree between ecosystem services showed distinct fluctuations across regions with varying urbanization levels. The undeveloped area had rich natural landscapes and provided prominent regulating services. Developing peri-urban areas are often characterized by a mosaic of land uses, including agriculture, common land and forest, alongside industry, urban infrastructure and informal settlements (Dolley et al. 2020). Also, due to the relatively high vegetation coverage and adjacency to the urban densely populated areas, peri-urban areas played a crucial role in regulating and maintaining ecological processes and life-support services for human welfare (Marshall et al.2018). As for the urban center, landscapes were dominated by built-up land, accompanied with public facilities and green urban infrastructure. Decision-makers could offset the loss of natural landscapes by constructing more convenient traffic networks, enabling residents to have easier access to these sites (Li et al. 2016). We believe that focusing on the rural-centric dynamic of ecosystem service trade-offs can emphasize the close connection between urbanization processes and ecosystems that span or interact across the traditional boundaries between developing and developed areas, and also highlight the rural-urban interaction arising around urbanizing regions from small towns to metropolis and urban corridors (Elmqvist et al. 2013).

4.4 Caveats and limitations

We want to make clear about the expressions or the names of the ecosystem service trade-off clusters in this study. They do have similar characteristics as the related concepts, 'ES bundles' including spatial coincidence, temporal synchronicity and causal interrelation (Berry et al. 2016). Yet we adopted the 'dominated function-related trade-off' expression because, on the one side, more associated ecosystem services need to be considered for concluding the ES bundles of a given region. Besides, we feel there should be a stronger emphasis on the inherent relationships (synergies or trade-offs) between ecosystem services to mitigate detrimental trade-offs and promote multifunctionality in landscape management.

As with all results of the ES measurement, there has been much debate on the accuracy of sampling methods. And the variety in the spatial level, indicator selection, and data collection may lead to different results (Peng et al. 2017; Seppelt et al. 2011). For example, the computing of carbon storage in this study was based on NPP with no appreciation of the soil carbon; air pollutant removal was simply measured by PM2.5 without consideration of other pollutants such as SO_2 or PM10. Besides, we analyzed the trade-off degree of paired ecosystems in varying urbanized regions to explore the relationships between them. However, what we have recognized is the relative strength and weakness of the paired ecosystem services, but we did not define the trade-offs or synergies with detailed interactions such as win-win or lose-lose synergies, a win-lose or lose-win trade-offs (Li et al. 2016). For decision-making and management purposes, it is of utmost importance to obtain quantitative knowledge about how human occupation and development affect ecosystem functions and services (Cumming et al. 2014; Miles et al. 2019; Peng et al. 2017), and a time-series analysis will be useful to build more comprehensive pictures about urbanization, land-cover change, ecosystem services trade-offs, synergies and losses (Lyu et al. 2018).

5 Conclusions

The present study developed quantitative indices to evaluate ecosystem services states and described their spatial distribution and interactions across an intensively human-dominated urban region. In summary, there was a strong tendency for provisioning to form trade-offs with regulating services and regulating and cultural services to form both trade-offs and synergies. The quantified ecosystem services showed heterogeneous and non-random spatial patterns and formed four multivariate cluster types with distinct composition. The cluster types showed dominant agricultural production in the northern plain, the high value of cultural services in the central urbanized areas, the multifunctional mix-used zones around central cities and mountainous forest with high ecological integrity in the southwestern area. The distribution of cluster types demonstrated spatial gradients associated with urbanization levels, yet the geographic patterns of cluster identified can be easily influenced by the selected ecosystem services and the data collected to measure these services. This study provides a proof-of-concept that interactions among multiple ecosystem services are associated with the socio-economic development and social-ecological land-use dynamics; useful insights that should be taken into consideration in future landscape planning.

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Ethics approval (include appropriate approvals or waivers): Not applicable

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