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Mapping Ecosystem Service Supply–Demand Bundles for an Integrated Analysis of Tradeoffs in an Urban Agglomeration of China

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Abstract: Ecosystem service (ES) bundles are widely used approaches to analyze ES tradeoffs in urban agglomeration. However, few ES bundle studies considered both the supply and demand sided. The objective of this study was to map ES supply–demand bundles to comprehensively analyze the ES tradeoffs in the Yangtze River Delta using cluster analysis, correlation analysis, hotspot analysis, and principal component analysis. We found that: (1) Both the supply and demand of ES are unevenly distributed with highly spatial autocorrelation. (2) There are significant tradeoffs and synergies between ES in terms of supply–supply, demand–demand, and supply–demand. (3) Four ES supply–demand bundle types were identified with distinct ES supply and demand relationships. (4) Land-use types, urban intensity, and climatic factors are the main social-ecological factors that distinguish the four identified clusters. The identified ES supply–demand clusters can support the main functional zoning of the Yangtze River Delta. Our results also suggest that land sharing is a more appropriate approach for the sustainable development of the Yangtze River Delta considering the balance of multiple ES supply and ES demand.

Keywords: ecosystem services; urban agglomeration; supply–demand bundles; urban sustainability; landscape sustainability; Yangtze River Delta

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1. Introduction

A great challenge faced by humans in achieving landscape sustainability is coping with the tradeoffs and synergistic relationships in multiple ES in complex human–environmental systems [1,2]. Under ES tradeoffs, one ES type decreases with any increase in another ES type, whereas ES synergy indicates that two ES types increase or decrease at the same time [3]. ES is also a cascading concept that connects the natural ecosystem to society's demands [4,5]. It includes not only ecosystems' capacity to supply ES based on their ecological functions (ES supply) but also humans' dependence on them for good quality of life (ES demand) [6]. Traditional ES tradeoff analysis mainly focuses on ES supply [7]. Mouchet et al. [8] proposed a more comprehensive typology of ES tradeoffs that includes three aspects: (1) tradeoffs in the simultaneous provision of ES; (2) tradeoffs between ES supply and ES demand; and (3) tradeoffs between different ES demands of stakeholders. This new typology considered both ES supply and ES demand and is more useful for transdisciplinary landscape planning and management.

ES bundle refers to "a set of related ES that recurs in different times or spaces" [9] and is a popular approach for analyzing ES associations [10]. Yet most current ES bundle studies focused on the ES supply. For example, Renard et al. [11] analyzed the historical dynamics of ES supply bundles in Quebec, Canada; Zhao et al. [12] mapped the ES supply bundles in an urban agglomeration in China; and Haberman and Bennett [13] analyzed ES supply bundles at the global scale. Few studies have analyzed ES bundles by considering both ES supply and ES demand, but ES supply–demand bundles can in fact have important advantages for the comprehensive analysis of the tradeoffs between ES that consider both ecosystem processes and human demands.

Recently, some scholars have started to consider ES demand in ES bundle studies. For example, Zoderer et al. [14] investigated social perceptions to represent the demand side in ES bundles. Li et al. [15] quantified ES supply–demand budget bundles for the Jinan metropolitan area in China. Baro et al. [16] analyzed the ES supply–demand bundles along the urbanization gradient of Barcelona. However, the focus of existing research has been on identifying the different social values of ES bundles [14,17]. Few researchers have analyzed ES tradeoffs in an integrated manner from the ES supply–demand bundle perspective. Thus, the knowledge gap in this research suggested comprehensively analyzing ES tradeoffs by considering both ES supply and demand.

Mapping ES supply–demand bundles is particularly important for urban agglomerations (a highly developed spatial form of integrated cities that occurs when the relationships among cities shift from mainly competition to both competition and cooperation) like the Yangtze River Delta (YRD) where ES tradeoffs are widespread [18]. On one hand, the YRD is undergoing rapid urbanization, and rapid land-use changes can lead to ES supply tradeoffs. On the other hand, there is usually a widespread supply–demand mismatch in the YRD, with excess demand in densely populated areas and excess supply in remote areas [19]. Thus, mapping ES supply–demand bundles in these regions can help policy makers better understand the complex linkages among multiple ES and develop sustainable development strategies for enhancing ES synergies and reducing tradeoffs. In the YRD, several studies have assessed the ES spatial patterns [20], ES dynamics and drivers [20], ES supply tradeoffs [20], and supply–demand mismatches [21]. However, to the best of our knowledge, no study has explored the ES supply–demand bundles in this region.

In this study, we intend to map ES supply–demand bundles to support sustainability policies in the urban agglomeration of the YRD. We will address the following three questions: (1) What are the relationships between ES (supply–supply, supply–demand, and demand–demand) in the urban agglomeration? (2) What ES supply–demand bundles can emerge from urban agglomeration, and how can different bundles be explained by social-ecological determinants? (3) How can policies be improved to promote the sustainability of the urban agglomeration?

2. Materials and Methods

2.1. Study Area

The Yangtze River Delta (YRD) urban agglomeration is located in the downstream area of the Yangtze River in China, with many coastal ports along the river (Figure 1). The YRD is composed of Shanghai and 25 prefecture-level cities in Jiangsu, Zhejiang, and Anhui provinces with an area of 211,700 km^2. The climate of the YRD belongs to the subtropical monsoonal zone, with an average annual temperature of 13 °C–19 °C and annual precipitation of 1000–1800 mm. The terrain of the YRD is mainly plains in the north and mountains and hills in the south with an average altitude of 88 m. The YRD has developed into one of the most densely populated, fastest urbanizing, and most economically developed regions in China over the past 30 years [22]. This area accounts for only 2.3% of the total area of the country but has a population of 225 million, and contributes about 1/4 of the country's gross domestic product (GDP) [23]. Over the past few decades, the rapid development of the Yangtze River Delta region has greatly improved the well-being of its inhabitants but has also degraded the local ecosystem and associated ES. How to protect local ES while developing the economy is a huge challenge in this region.

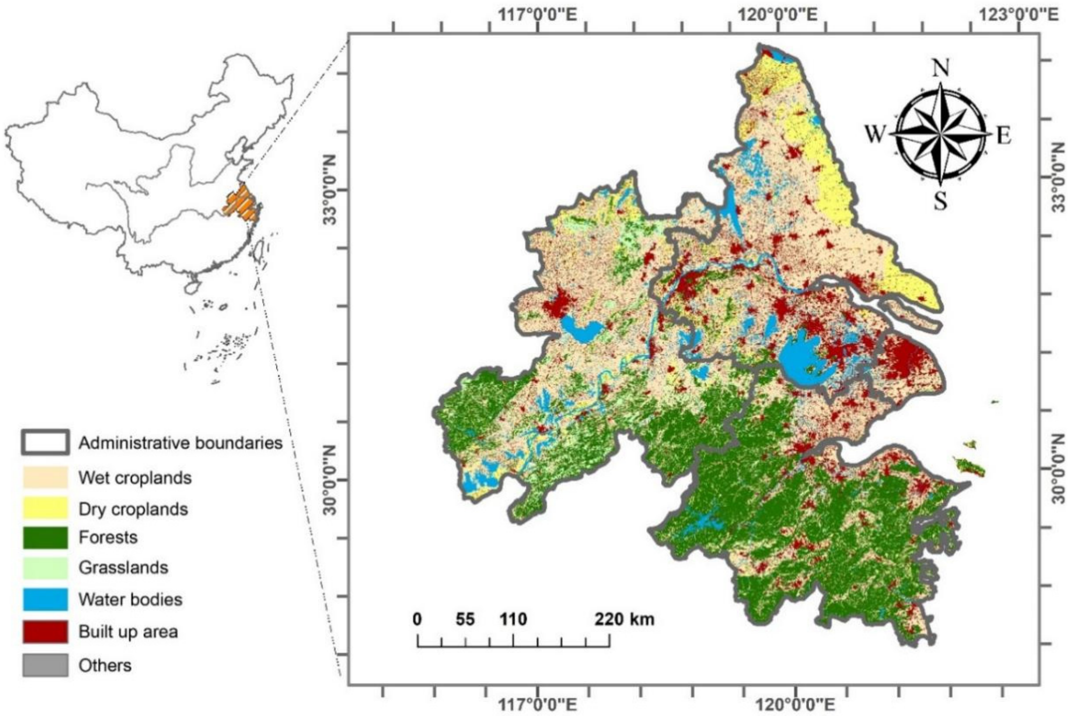

Figure 1. The location and land use of the study area.

2.2. Data Collection and Processing

The food provisioning service data (including grain, meat, and aquatic) were obtained from the Statistical Year Book (https://csjnjk.cei.cn/jsps/Default, accessed on 15 January 2021). The net primary productivity (NPP) data were derived from the MODIS 8-day synthetic data (MOD17A3H) product with a spatial resolution of 500 m for the period 2001–2020. ET was derived from the Modis 8-day synthetic data (MODIS16A2) product with a spatial resolution of 500 m. Soil data with 1 km spatial resolution were obtained from the World Soil Database (http://www.fao.org/soils-portal/data-hub, accessed on 15 January 2021). The population data with 1 km spatial resolution for 2000–2020 were from Landscan (https://landscan.ornl.gov/, accessed on 15 January 2021). Meteorological data (including rainfall, temperature, wind speed, and relative humidity) were obtained from the China Meteorological Centre (http://cdc.cma.gov.cn, accessed on 15 January 2021). We obtained the land use/cover change (LUCC) map (30 m) of 2020 from the Data Center of Resource and Environmental Science (http://www.resdc.cn, accessed on 15 January 2021). The soil hydrology groups data for this study were obtained from the official Earth Data website (https://earthdata.nasa.gov/, accessed on 15 January 2021). Air quality data ertr obtained from the World Air Quality Index Project Team (https://aqicn.org/city, accessed on 15 January 2021).

2.3. Ecosystem Service Selection and Quantification

We selected eight ES in this study based on their relevance to the YRD, covering all the categories of ES, and data availability, including (1) crop production, (2) meat production, (3) aquatic production, (4) urban cooling, (5) air purification, (6) flood risk mitigation, (7) carbon sequestration, and (8) outdoor recreation. We acknowledge that biodiversity/species diversity is important in determining the ES that can support the sustainability of a region. However, we did not consider biodiversity in this study for two reasons: (1) large-scale biodiversity data such as for the YRD are unavailable, and (2) biodiversity as a supporting service directly determines ecosystems' ability to deliver other ES, which could have led to double counting issues. All the ES supply and demand indicators were calculated for the year 2020 at a spatial resolution of 1 km. The indicators and quantification methods of each selected ES are summarized in Table 1.

Table 1. The indicators and quantification methods of the selected ES.

Ecosystem Services	Indicators	Quantification Methods
Grain production	Supply: Grain production capacity Demand: Grain consumption	Grain production data obtained from the Statistical Year Book Product of population and daily grain consumption per person
Meat production	Supply: meat production capacity Demand: meat consumption	Meat production data obtained from the Statistical Year Book Product of population and daily meat consumption per person
Aquatic production	Supply: Aquatic production capacity Demand: Aquatic consumption	Aquatic production data obtained from the Statistical Year Book Product of population and daily aquatic consumption per person
Urban cooling	Supply: Urban cooling capacity Demand: heatwaves	Urban InVEST model [24] The number of days with the maximum daily temperature greater than 35 °C (the high-temperature standard in China).
Air purification	Supply: PM2.5 purification capacity Demand: Air pollution risk	Relationship between pollutant deposition rate and wind speed in different land cover types [25]. Number of days with PM2.5 concentration greater than 100 μg/m^3 (EPA PM2.5 pollution criteria) in a year
Flood risk mitigation	Supply: Runoff retention capacity Demand: Runoffs	Urban InVEST model [26] Runoffs need to be mitigated, calculated by the Urban InVEST model [26]
Carbon sequestration	Supply: NPP Demand: Carbon emissions	Modis NPP data County-level carbon emission inventories from the Chinese Bureau of Statistics
Outdoor recreation	Supply: Outdoor recreation capacity Demand: Accessible population	Recreation capacity was mapped based on three components: naturalness, nature reserve, and water. Outdoor recreation demand was determined by the accessibility and population density [27]

2.3.1. Ecosystem Service Supply Quantification

The food provisioning services (including grain, meat, and aquatic) are quantified based on the production data from the Statistical Year Book. Carbon sequestration indicates the ability of vegetation to absorb CO_2 in the air. Here we use NPP as a proxy of carbon sequestration capacity. The remaining ES supply indicators are calculated as follows:

Urban cooling supply refers to the cooling capacity (CC) of the vegetation to mitigate urban heat island effects [24]. In InVEST, cooling capacity is modeled considering three components: shading (S), evapotranspiration (ET), and albedo (A) (1).

$$CC = 0.6S + 0.2A + 0.2ET \tag{1}$$

The primary input in this model is a LUCC map. The parameters of each LULC class include evapotranspiration coefficient (Kc), albedo, cooling distance, and green area (Table S1). The kc values assigned to each LUCC class were from existing guidance [28]. Albedo values were also obtained from existing studies [29,30]. The reference air temperature was set to the minimum air temperature observed in the suburbs of each city. The study used the difference between the average daily maximum temperature from June to August within the urban boundary and the average daily temperature from June to August in the suburbs to represent the urban heat island (UHI) intensity.

Flood risk mitigation supply refers to the capacity of vegetation to reduce runoff production (Hamel et al., 2021). We used the urban InVEST model to calculate the runoff reduction. The InVEST model is designed to calculate greenspace's ability to reduce runoff during storms. We estimated the runoff using the SCS curve method.

$$Q_{p,i} = \begin{cases} \frac{(P-\lambda S_{max_i})^2}{P+(1-\lambda)S_{max,i}} & \text{if } p > \lambda \cdot S_{max,i} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where P is the storm depth, indicating the potential retention, and λS_{max_i} is the initiate runoff depth (λ = 0.2).

$$S_{max,i} = \frac{25400}{CN_i} - 254 \tag{3}$$

λS_{max_i} is the curve number function, CN is the curve values of rainfall-runoff for different LULC types in each hydrologic soil group (NRCS 2004).

The parameter assigned to each LUCC class is CN. According to the description in the INVEST user manual. CN data was determined by referring to the USDA article "Urban Hydrology for Small Watersheds" [31] and based on the actual conditions in the Yangtze River Delta region (Table S2).

Rainfall depths in this study were taken as the average of the maximum single-day rainfall (mm) for the year 2020 at the meteorological station sites in the Yangtze Delta region for the hypothetical rainfall event, which is about 86.78 mm.

Air purification supply refers to the capacity greenspace can provide to filter air pollution (Nowak et al., 2013). This study mainly considers the PM2.5 (a major pollutant in the YRD region) purification capacity of ecosystems based on the empirical relationship between PM2.5 deposition rate and wind speed in different land cover (Pistocchi et al., 2010). The PM2.5 deposition velocity of soil and water has a linear relationship with wind speed; The PM2.5 deposition velocity of the forest has a linear relationship with the wind speed, and its slope and intercept have a linear relationship with the relative humidity [25].

$$L_{forest} = kx + b \tag{4}$$

$$k = 0.0015 \times forest\% + (0.0005 \times (1 - forest\%)) \tag{5}$$

$$b = 0.002 \times (1 - forest\%) \tag{6}$$

$$L_{soil} = 0.0005x + 0.002 \tag{7}$$

$$L_{water} = 0.0009x + 0.0004. \tag{8}$$

where x is the wind speed (m/s), L_{forest} is the forest land-use type, b is the intercept, k is the slope, forest% is the relative humidity of the forest, L_{soil} is the bare soil land-use type, L_{water} is the water body.

Outdoor recreation supply refers to the recreational opportunities provided by ecosystems. We considered the following three dimensions in calculating recreational opportunities: naturalness, nature conservation, and water (Paracchini et al., 2014). One or several factors were used in each component considering their relevance to the YRD and data availability (Table S3). A distance decay function was used to determine the assigned score of water factors, with the assumption that the recreation capacity of water decreases with the increased distance from the water.

The degree of naturalness of different land-use types was based on Bing et al. [32]. Nature protection in this study refers to areas designated as nature reserves or natural parks [32]. The distance decay function of the water dimension was determined by Baro, Palomo, Zulian, Vizcaino, Haase, and Gomez-Baggethun [27].

2.3.2. Ecosystem Service Demand Quantification

ES demand can be classified into (1) risk reduction, (2) preferences, (3) direct use, and (4) consumption [6]. In this study, we quantified food demand (crop, meat, and aquatic) by the product of population and daily food consumption per person. We quantified the urban cooling demand using the number of days with a maximum daily temperature greater than 35 °C (the high-temperature standard in China). We quantified the flood risk mitigation demand using the runoffs that need to be mitigated in the rainstorm. We quantified the air purification demand using the number of days of PM2.5 pollution in a year. According to the U.S. Environmental Protection Agency (EPA) criteria, when PM2.5 concentration is greater than 100 μg/m^3, the air may negatively affect human health. So we use 100 μg/m^3 as a threshold value of PM2.5 pollution. Outdoor recreation demand values were obtained from a cross-tabulation matrix between a reclassified raster of Euclidian distances to recreation sites and the population density grid [27] with the assumption that all inhabitants in the case study area have similar desires in terms of outdoor recreational opportunities but that their level of fulfillment depends on proximity to recreation sites. The recreation sites refer to the medium- to very-high-capacity recreation areas (i.e., recreation capacity equal to or higher than 0.33) assuming that inhabitants want to reach these areas and not low-capacity areas (recreation capacity lower than 0.33, mostly corresponding to artificial land cover). The classification of population density and distance to recreation sites was referenced [27].

2.4. Quantify the Spatial Distributions and Tradeoffs among ES

We quantified all ES indicators at the county (n = 164) level. Counties are not only important administrative units for ES management but also the smallest units for which statistical data are available. ES indicators for each county were averaged by area for comparison between counties, and each ES supply and demand indicator was normalized to 0–1 y using the max-min method. To reflect the spatial distribution of the overall ES supply and ES demand, we aggregated all the individual ES using equal weights, with the assumption that all ES are equally important. To test the spatial autocorrelation, we calculated the global Moran's I for the aggregated ES supply and ES demand. When the z-score of Moran's I is greater than 1.96, it indicates the presence of significant spatial clustering. Getis-Ord Gi* hotspot analysis was also performed in ArcGIS to identify hot and cold spots of the aggregated ES supply and aggregated ES demand [33]. Hot/cold spots with 90%, 95%, and 99% confidence were reported in this study. We also calculated the Simpson Index to show the evenness of ES supply and demand across counties.

We followed a unified framework proposed by Mouchet, Lamarque, Martín-López, Crouzat, Gos, Byczek, and Lavorel [8] to analyze ES tradeoffs (Figure 2). In this framework, we analyzed three broad types of ES tradeoffs considering both ES supply and ES demand. For the supply–supply tradeoff, we analyzed how one ES supply correlates with the other. For the supply–demand tradeoff, we analyzed whether ES supply and ES demand are spatially matched. For the demand–demand tradeoff, we analyzed how one ES demand is consistent or conflicting with the others. A Pearson parametric correlation test was first performed in R to examine the ES supply–supply, supply–demand, and demand–demand associations. Then, to identify the spatial mismatches of ES supply and demand, we also calculated the supply–demand ratio for each paired ES based on the following formula proposed by Li et al. [34]:

$$Y = \frac{S - D}{(S_{max} + D_{max})/2}, \begin{cases} > 0, \ surplus \\ = 0, \ balance \\ < 0, \ deficit \end{cases} \tag{9}$$

where Y refers to the ratio of ES supply to ES demand, S refers to ES supply, D refers to ES demand, and S_{max} and D_{max} refer to the ES supply maximum values and ES demand maximum values, respectively.

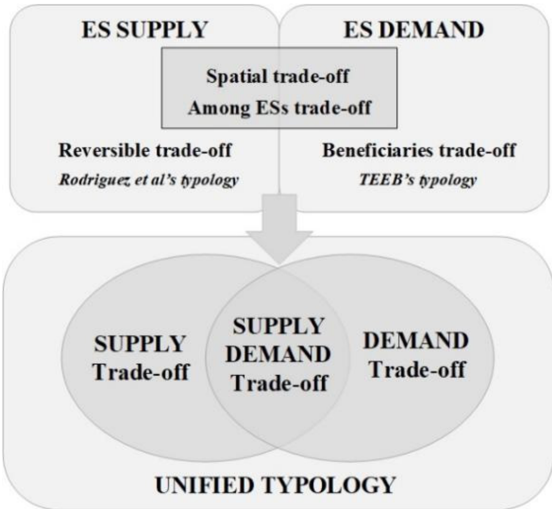

Figure 2. The unified ES tradeoff typology considered both the ES supply and ES demand (Modified from Mouchet, Lamarque, Martín-López, Crouzat, Gos, Byczek and Lavorel [8]).

2.5. Ecosystem Service Supply–Demand Bundles and Associated Driving Forces

Cluster analysis was used to identify bundles of counties with consistent tradeoffs among ES. We used K-means cluster analysis in R to identify the ES supply–demand bundles. We used the elbow method to choose the optimal number of clusters. The identified clusters were mapped using a flower diagram. Principal component analysis was used to quantitatively visualize the associations between all ES indicators in different clusters across the urban agglomeration. To analyze the driving forces of ES supply–demand bundles, we quantified nine social-ecological variables at the county scale, including four LUCC composition indicators (farmland, forest, grassland, and urban), two climatic factors (precipitation and temperature), two socioeconomic indicators (population and GDP per capita), and one air pollution indicators (PM 2.5 concentration). The Wilcoxon test was performed in R to compare these indicators among different ES supply–demand clusters.

3. Results

3.1. Spatial Distribution of ES Supply and Demand

All the ES supply indicators are spatially autocorrelated in the Yangtze River Delta (YRD), with all z-scores greater than 1.96 (Figure 3). The distribution of all ES supply indicators is spatially heterogeneous. The high-value areas of ES supply are mainly located in the northern and southern parts of the YRD (Figure 3i), with food production and meat production dominating in the northern part (Figure 3a,b) and urban cooling, flood risk mitigation, and carbon sequestration dominating in the southern part (Figure 3d–f). In addition, the high-value areas for air purification capacity are mainly located in the western and southern regions of the YRD (Figure 3g), while high-value areas for outdoor recreation potential are mainly concentrated in the central and southern regions of the YRD (Figure 3h). The low-value areas of ES supply are mainly located in the areas around the Taihu Lake basin (Figure 3i).

All the ES demand indicators are spatially autocorrelated in the Yangtze River Delta (YRD), with all z-scores greater than 1.96 (Figure 4). Overall, the highest aggregated ES demand values are located in Shanghai and surrounding areas (Figure 4i). The high-value areas of crop consumption, meat consumption, aquatic consumption, carbon emissions, and outdoor recreation demand are consistent with those of the aggregated ES demand. However, the high-value areas for urban cooling demand, flood risk mitigation demand, and air purification demand are quite different from that of the aggregated ES demand, mainly located in the southern part, Shanghai surrounding areas and the northern part, and the northern part of the YRD, respectively.

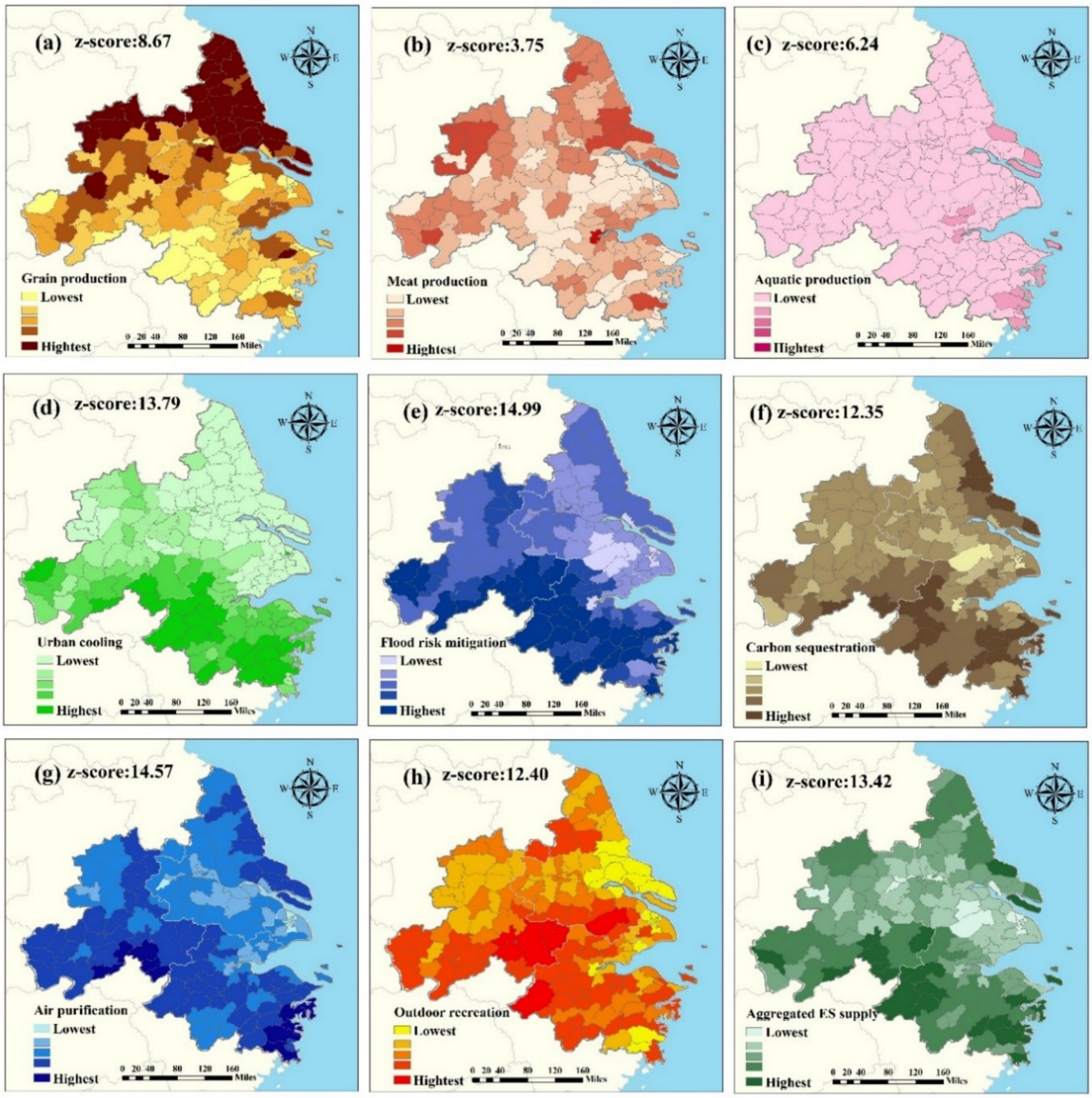

Figure 3. The spatial distributions of individual ES supply indicators (**a**–**h**) and aggregated ES supply capacity (**i**). The z-score values in each panel indicate the significance of spatial autocorrelation.

The hotspot analysis shows that the statistically significant hot spots (90% confidence) of aggregated ES supply are mainly located in the southern part of the YRD, while the cold spots of aggregated ES supply are mainly located in Shanghai and surrounding areas (Figure 5a). The locations of hot spots and cold spots of aggregated ES demand are spatially opposite to those of aggregated supply (Figure 5b). The hot spots of ES demand are mainly distributed around Shanghai, while the cold spots are mainly located in the southern part of the YRD. However, hotspots of ES supply and demand do not imply a high diversity of ES supply and demand (Figure 4c,d). The high ES supply Simpson indices are scattered distributed across the whole region, while the high ES demand Simpson indices are mainly located around the Taihu Lake basin, with sporadic distribution in other regions.

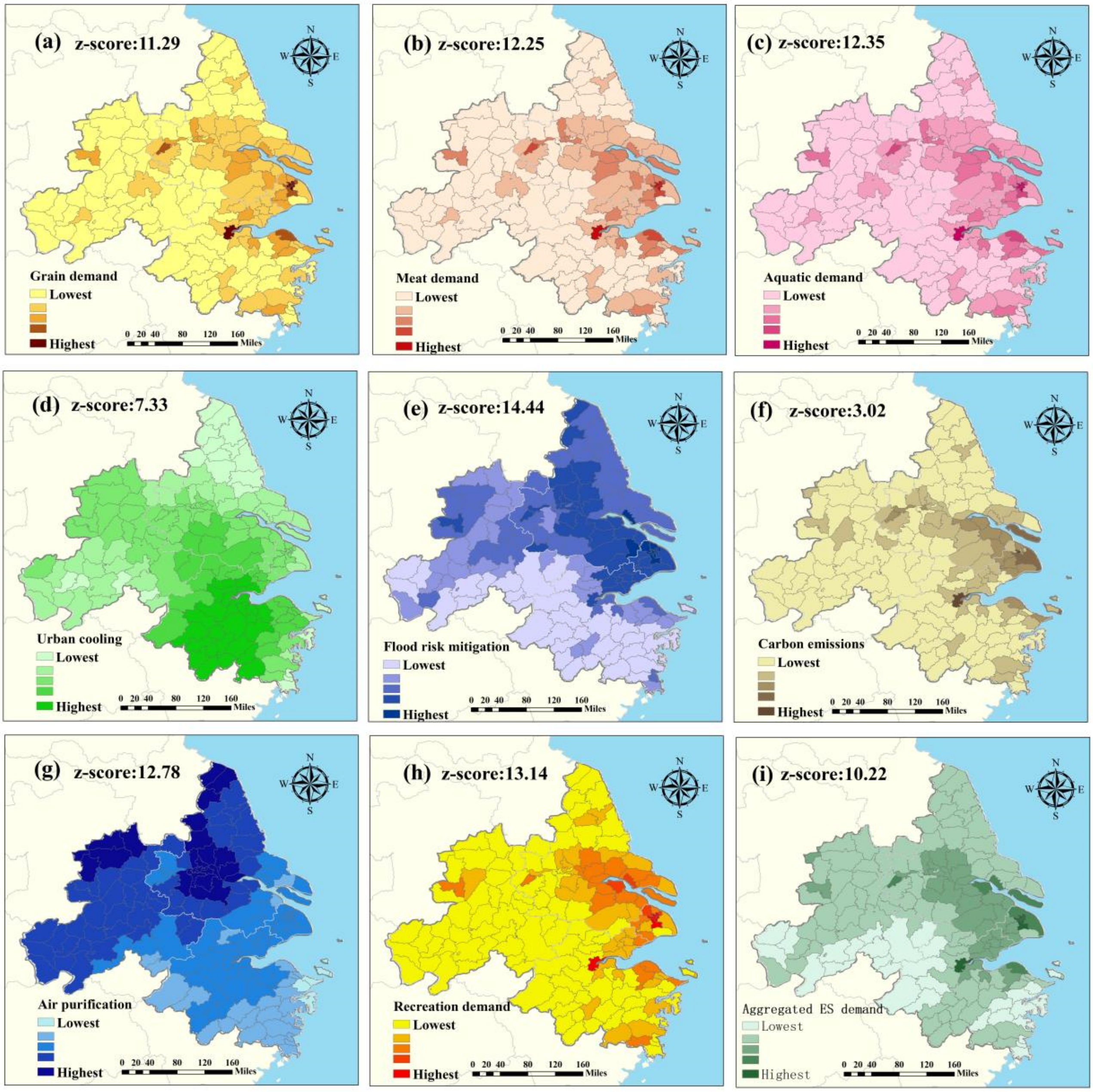

Figure 4. The spatial distributions of individual ES demand indicators (**a**–**h**) and aggregated ES demand capacity (**i**). The z-score values in each panel indicate the significance of spatial autocorrelation.

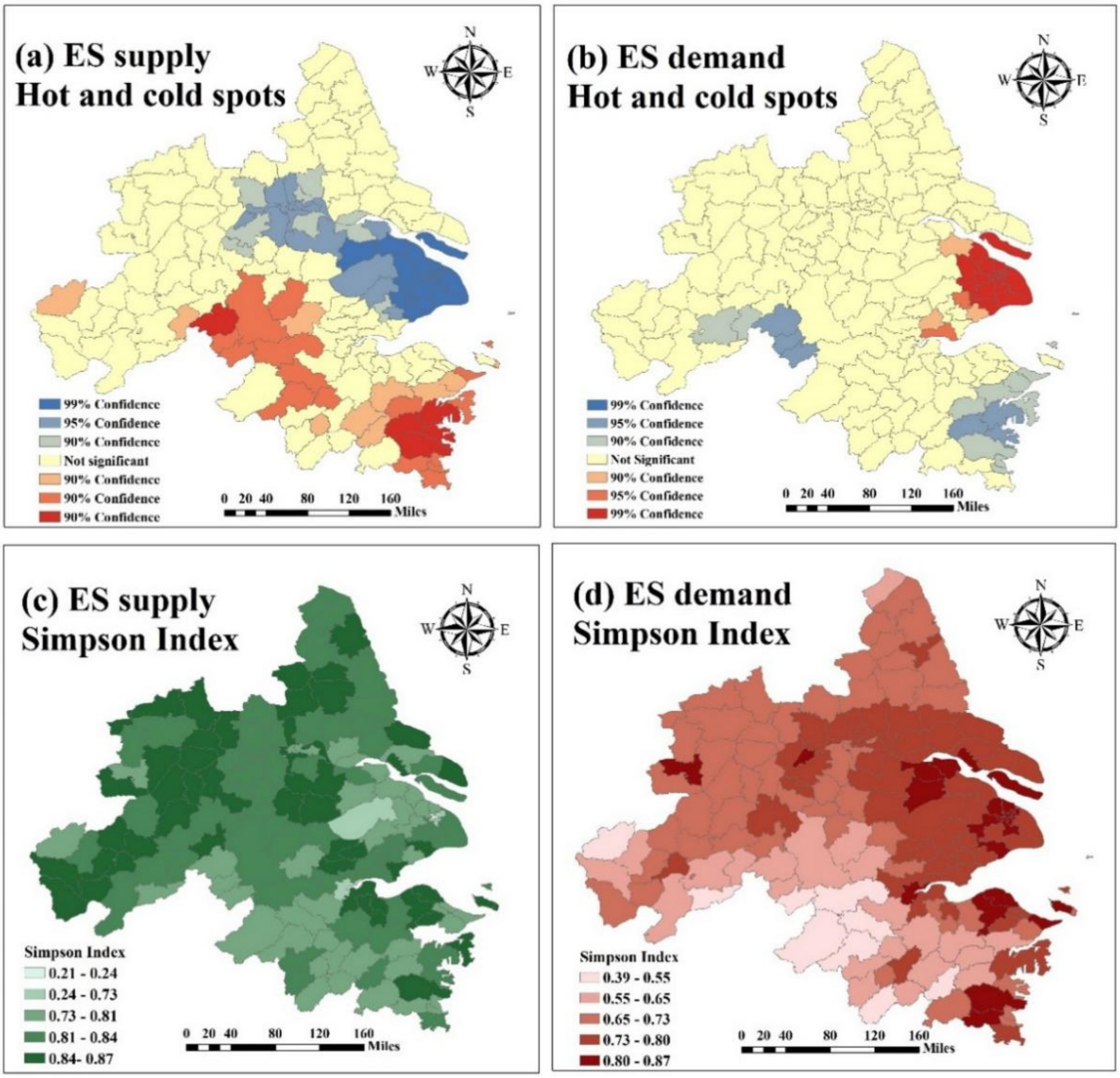

Figure 5. The hot/cold spots (**a**,**b**) and Simpson index (**c**,**d**) of ES supply and demand.

3.2. Interactions among Ecosystem Services

The associations between different ES supply indicators are complex (Figure 6). (1) For provisioning services, meat production is positively correlated with both grain production and aquatic production, while no significant correlations were found between grain production and aquatic production. (2) For regulating and cultural services, all the ES supply indicators, including air purification, carbon sequestration, urban cooling, flood risk mitigation, and outdoor recreation, are positively correlated with each other ($p < 0.05$). (3) The relationship between provisioning services and non-provisioning services is inconsistent. Grain production shows significant negative correlations with urban cooling, flood risk mitigation, and outdoor recreation. Meat production shows significant negative correlations with urban cooling and outdoor recreation. Aquatic production shows negative correlations with air purification and carbon sequestration.

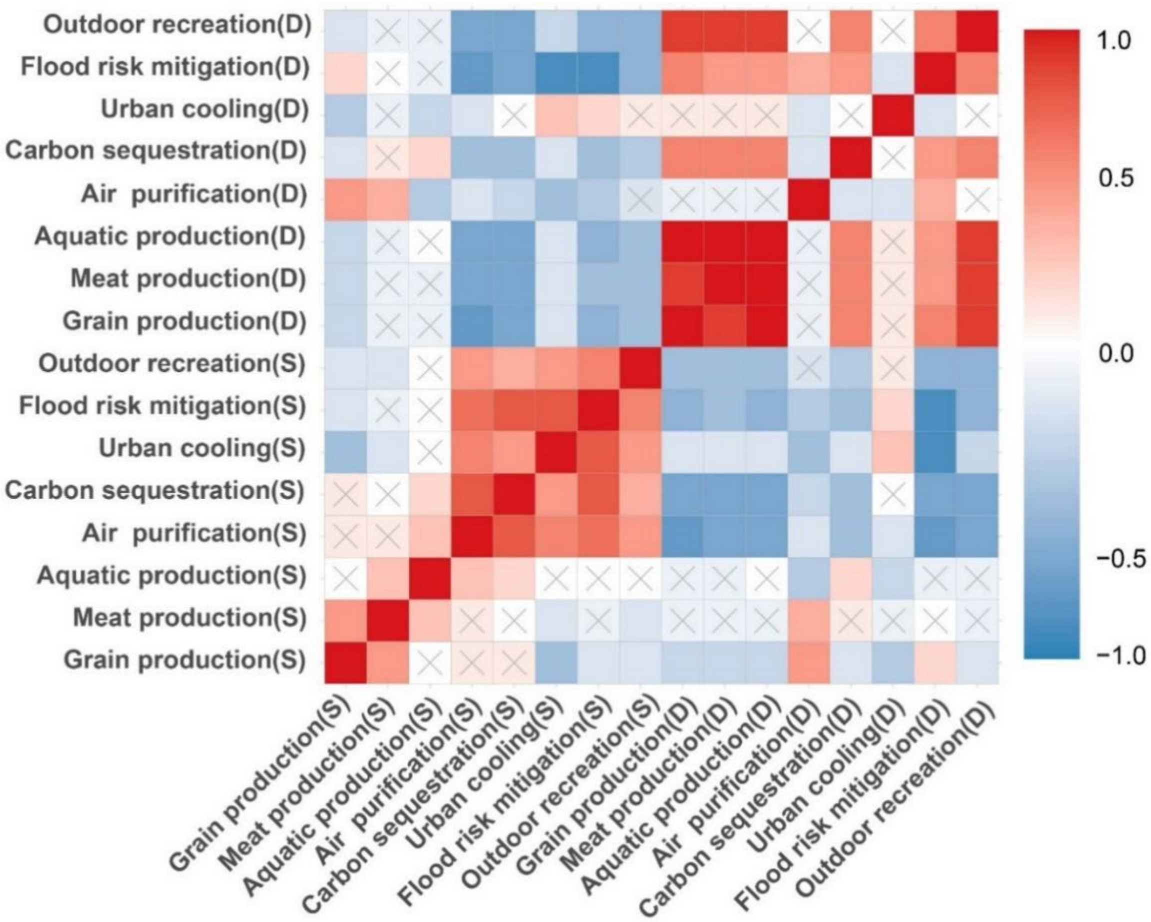

Figure 6. The Pearson correlation matrix of all the sixteen ES supply and demand indicators. The "×" indicates non-significant relationship ($p > 0.05$).

The relationships between ES demand indicators are less complex than that of ES supply indicators (Figure 6). Grain consumption, meat consumption, aquatic consumption, carbon emissions, flood risk mitigation demand, and outdoor recreation demand are positively correlated with each other ($p < 0.05$). Interestingly, urban cooling demand is negatively correlated with air purification demand and flood risk mitigation demand ($p < 0.05$), and air purification demand is negatively correlated with carbon emissions and is positively correlated with flood risk mitigation demand ($p < 0.05$). Most ES demand indicators are negatively correlated with ES supply indicators (Figure 6). But there are also some exceptions, for example, air purification demand is positively correlated with grain production and meat production. Carbon emission is positively correlated with aquatic production. Urban cooling demand is positively correlated with urban cooling supply and flood risk mitigation supply. Flood risk mitigation demand is positively correlated with grain production.

Mismatches widely existed between each paired ES supply and demand indicator (Figure 7). For regulating and cultural services, the areas of a supply–demand mismatch for all paired ES exceed 75%. Excess demand is the dominant mismatch type for urban cooling and air purification, and excess supply is the dominant mismatch type for carbon sequestration and outdoor recreation, while for flood risk mitigation, excess demand and excess supply occupy roughly the same areas. For crop production, meat production, and aquatic production, ES supply–demand balance and excess supply occupied most of the regions.

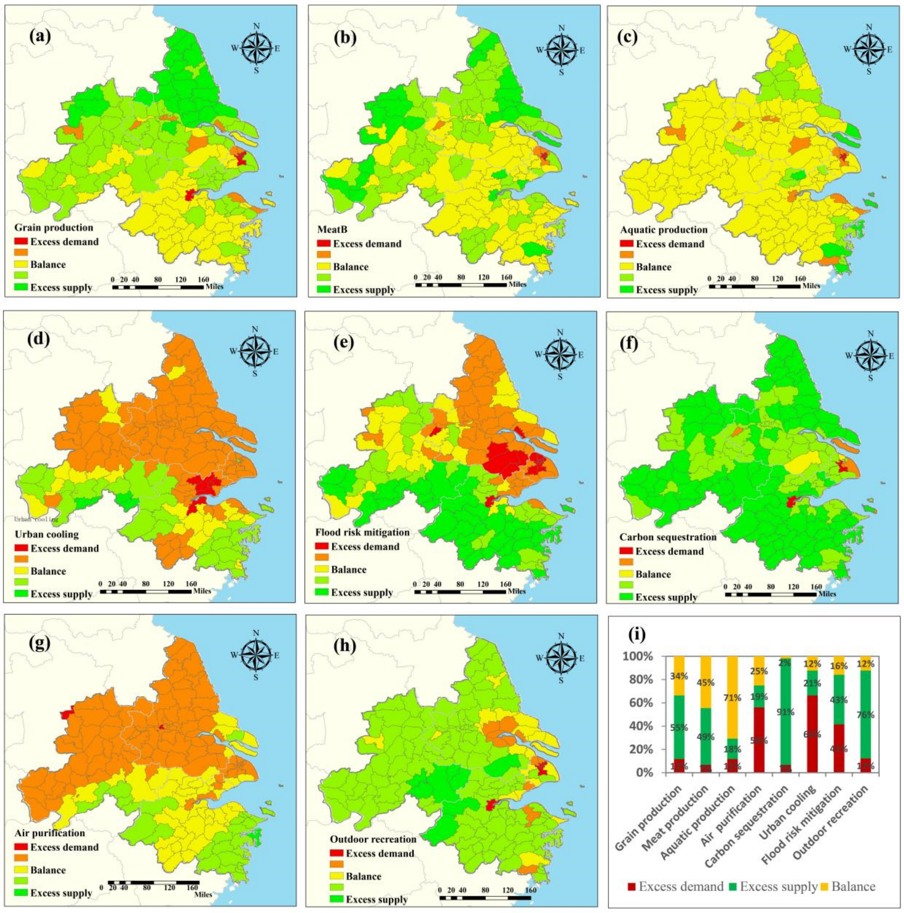

Figure 7. The spatial patterns of paired ES supply–demand ratios (**a**–**h**) and the proportion of each relationship type for the eight ES (**i**).

3.3. ES Supply–Demand Bundles and Associated Driving Forces

The k-means cluster results showed that all the ES indicators of the 164 counties in the YRD can be classified into four clusters, indicating four ES supply–demand bundles (Figure 8). Moran's I indicated that there was spatial autocorrelation between these four ES supply–demand bundles.

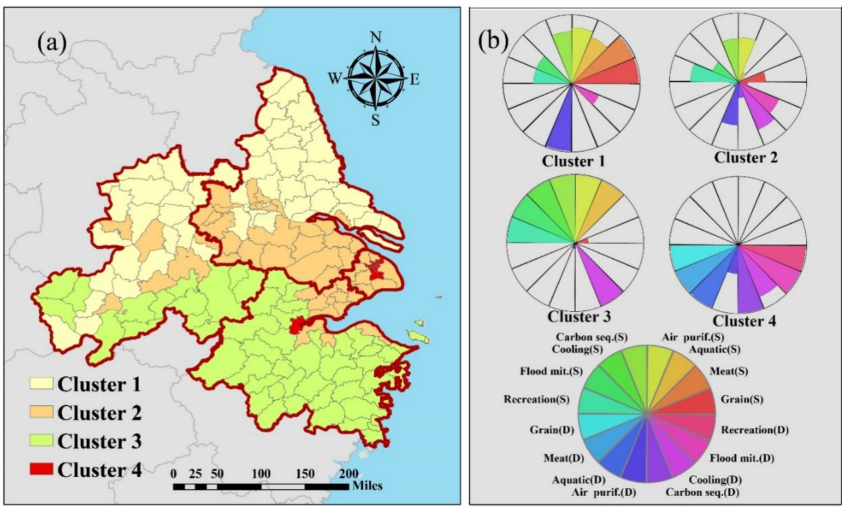

Figure 8. Spatial distribution of ES supply–demand bundles (**a**) and flower diagrams for each identified cluster (**b**).

The four ES supply–demand bundles were named and described according to the ES supply–demand associations occurring in each cluster (Figure 8b) and the main social-ecological characteristics in each group. (1) Cluster 1 (n = 48) was named "food silos", which combines those counties where land use is predominantly farmland and is located in most agricultural areas of Anhui and Jiangsu provinces. In this cluster, grain production and meat production capacity show high values, while other ES supply indicators show low to moderate values. Almost all the ES demand indicators show low values, except for air purification demand. (2) Cluster 2 (n = 49) was named secondary cores and included counties with moderate populations and economic development levels, mostly located near the core of the YRD urban agglomeration. In this cluster, various ES indicators are balanced with moderate values. (3) Cluster 3 (n = 58) was named the "ecological backyard" because it is mostly covered by forests, where there is usually a small urban population and no or little arable land. This cluster shows the highest values for non-provisioning service supply and the lowest values for most ES demand indicators, with only the highest value for urban cooling demand. (4) Cluster 4 (n = 7) was named "main" cores because it includes the main urban area of Shanghai. The population, urbanization, and economic development levels in this cluster are the highest. The ES supply of this cluster is the lowest for all ES types, while ES demand is the highest. This cluster is in the opposite direction of the ecological backyard cluster in terms of ES supply and demand.

The PCA results showed that the first two principal components explained 65.6% of the variance in the group of 16 ES indicators (Figure 9). The first axis (45.9%) indicates the tradeoff between most non-provisioning ES supply indicators and most ES demand indicators, with the exception of demand for urban cooling and air purification, which contributes to PC2. The second axis (19.7%) mainly shows a tradeoff between food supply and most other ES supply and demand indicators.

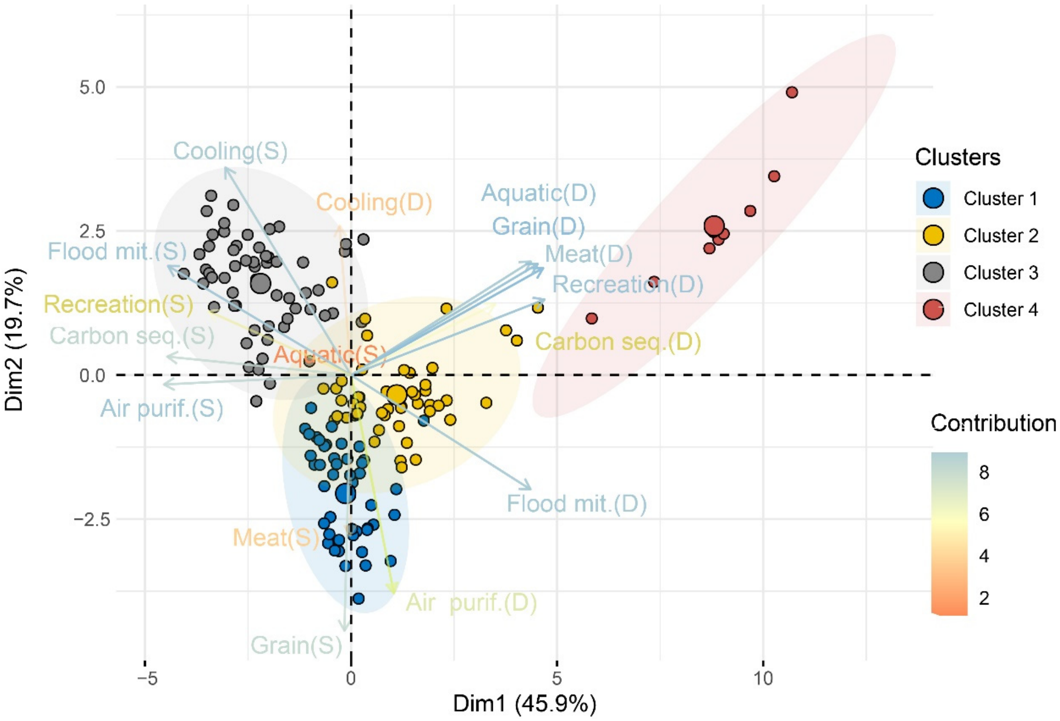

Figure 9. Principal component analysis results for the ES supply and demand indicators within each cluster.

The human–environmental characteristics of the clusters differ significantly from one another (Figure 10). In terms of socioeconomic characteristics, Clusters 4 and 2 have significantly higher total populations, GDP per capita, and urban land area compared with Clusters 1and 3. For climatic indicators, Cluster 4 and Cluster 3 have higher temperatures than the other two clusters, while Cluster 1 has lower average annual precipitation than the other three clusters. For vegetation type indicators, the area of farmland area in Cluster 1 is significantly higher than that of the other three clusters, while the forestland and grassland areas are higher in Cluster 3 than in the other three clusters. In addition, the PM2.5 concentrations in Clusters 1 and 2 are significantly higher than those in Clusters 3 and 4.

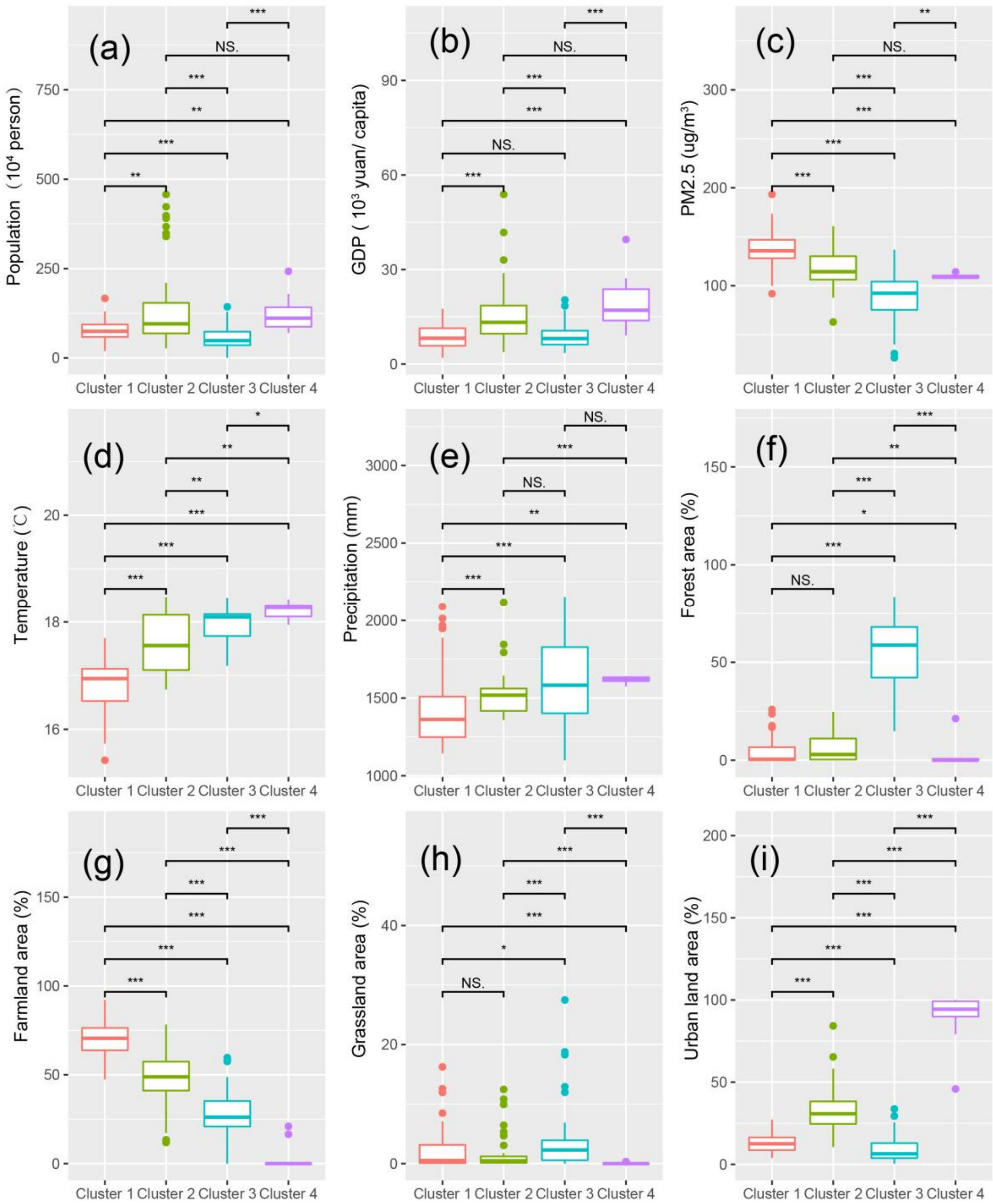

Figure 10. Differences in the human-environmental factors among the four identified clusters. (**a**–**i**) refers to Population, GDP, PM2.5, Temperature, Precipitation, Forest area, Farmland area, Grassland area, and Urban land area, respectively. Different symbols above the boxplots indicate significant different levels (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, NS. indicates no significance).

4. Discussion

4.1. Tradeoffs between ES Considering Both the Supply and Demand Sides

Our results suggest that on the supply side, there is a relatively strong synergistic relationship between regulating and cultural services but there are tradeoffs between provisioning services and other types of services (Figure 6). This is consistent with the findings of most ES tradeoff studies [35,36]. According to Bennett, Peterson, and Gordon [3], ES supply tradeoffs may be related to interactions between ES, or may be due to responses to the same driver of change. In the YRD, given the apparently different land-use conditions (Figure 10), the tradeoffs between food production services and other services are mainly due to the fact that they both respond to the drivers of land-use change.

In terms of ES demand, we found a significant synergistic relationship between food consumption, carbon emissions, flood risk mitigation demand, and outdoor recreation demand (Figure 6). This is consistent with the results of a similar study in the Barcelona metropolitan region [16]. The possible reason for this synergistic relationship is that the demand for these services is strongly associated with population density and economic development. Interestingly, we also found significant tradeoffs between ES demands (e.g., urban cooling-air purification, carbon emissions-air purification, and flood risk mitigation-urban cooling). These ES demand indicators are represented by the environmental risks that need to be mitigated. For example, heat waves indicate urban cooling demand, air pollution intensity indicates air purification demand. The negative correlation between these environment risk distributions leads to a tradeoff in ES demand.

Most ES supply indicators show a tradeoff with ES demand indicators (Figure 6), i.e., high ES demand leads to a decrease in ES supply capacity. These results could explain why ES supply–demand mismatches widely exist [37–39]. The main reason for this tradeoff is mainly human-induced land-use changes. In the areas of high ES demand, large populations have converted much of the natural land to impervious surfaces, thereby reducing ES supply (Figure 10). It is worth noting that not all ES demand has a tradeoff with ES supply, and some ES demand shows synergy with ES supply, such as the relationship between air purification demand and grain production, carbon emissions and fish production relationship, and urban cooling demand and flood risk mitigation supply. Regions with high food production capacity also happen to be the more developed industrial areas so there is a synergy between grain supply capacity and the air pollution. As CO_2 emissions are higher in the developed coastal areas and the fisheries are also more developed in the coastal areas so there is a synergy between fish production and CO_2 emissions. The high temperature areas happen to be the best vegetated areas in the Yangtze River Delta, so there is a synergy between the demand for urban cooling and the supply capacity for flood risk mitigation.

4.2. Ecosystem Service Bundles in the Yangtze River Delta

ES bundles could help to understand complex urban human–environmental systems that are difficult to analyze [14,40,41]. ES supply–demand bundles emphasize the linkages between ES supply, between ES demands, and between ES supply and demand. They encourage the consideration of the multiple tradeoffs and synergies involved in landscape management decisions [8]. ES supply–demand bundle studies differ from the traditional ES supply bundle studies in that they are more conducive to helping design landscape management strategies by combining multiple ES supplies with ES demands [15]. ES supply–demand bundle studies also differ from the widely studied ES supply–demand mismatch. Most ES supply–demand mismatch studies focus mainly on paired ES supply and demand [42], which is not conducive to identifying multiple ES supply–demand relationships. In contrast, ES supply–demand bundles can help identify not only the relationship between one ES supply and the demand of other ES types, but also the repetitive and consistent ES supply–demand relationship across landscapes.

In this study, we identified four ES supply–demand bundles across the study area (Figure 7), from which we can find an overall ES supply–demand pattern that is mainly determined by the land-use and socioeconomic conditions (Figure 10) specifically, by land-sparing vs land-sharing approaches [43]. The "main" cores, "food silos", and "ecological backyards" follow the land-sparing approach whose land-use diversity is low, whereas the "secondary" cores reflect more of a land-sharing approach with mixed land use. This general ES supply–demand pattern is a result of the rapid land-use changes in the YRD over the past few decades [21]. We also found the "food silos" counties have high food production capacity but a low capacity for other ES supply, while "ecological backyards" counties have a high potential for providing carbon sequences, urban cooling, flood risk mitigation, and outdoor recreation services. Other ES supply bundle studies have shown similar results [16,44]. These results suggest that regulating and cultural services have synergetic relationships, while provisioning services have tradeoff relationships with other services. Meanwhile, "food silos" counties and "ecological backyards" counties are less urbanized areas with low population density (Figure 10), suggesting that ES demand is lower in these regions. An exception is the air purification and urban cooling demand, which is not related to urbanization rates, but to climatic and pollutant factors, such as temperature and PM2.5 concentration. Thus, "food silos" counties located mainly in high polluted areas have substantially higher values of air purification demand, while "ecological backyards" counties located in areas with higher air temperature also have higher urban cooling demand. As expected, our ES supply–demand bundles also show that the densely populated "main core" counties show the largest ES demand and lowest ES supply. The largest ES supply–demand mismatch in this region is consistent with other studies [27,39]. In addition, "secondary core" counties with a mix of land-use types, thus show a balance between ES supply and ES demand.

4.3. Implications for Landscape Management and Planning in the Yangtze River Delta

Currently, the Yangtze River Delta is implementing an integrated development strategy that encourages close cooperation between cities in this region in terms of economic development and environmental protection. In this context, one of the main approaches of the integrated development strategy is the zoning of main functions. That is, the entire region is divided into ecological protection zones, agricultural zones, and urban development zones based on social-ecological characteristics. Our identified ES supply–demand bundles can work as a scientific basis for this zoning. The identified "food silos" counties can be categorized into agricultural zones, the "ecological backyards" counties can be categorized into "ecological land", the "main cores" counties can be categorized into the constrained develop area, and the "secondary cores" counties can be classified as an important area for urban development.

In addition, our results support the "land sharing" strategy for urban development from the perspective of ES supply–demand relationships. In the "land sparing" approach, ES demand and ES supply are highly mismatched. In our case, the "main core" counties have the highest ES demand and lowest ES supply capacities, while the "food silos" and "ecological backyards" counties have somewhat the highest ES supply capacity, but the lowest ES demand capacity. It has been argued that the ES can be imported from rich ES supply areas to the highest ES demand area. For some ES types, this approach is possible, such as food production, and carbon sequestration. However, there are many ES that are produced and used in local counties, such as outdoor recreation, air purification, flood risk mitigation, and urban cooling. These ES cannot be imported from remote areas. To fully achieve a balance between supply and demand for ES, we highly recommend the "secondary cores" mode with moderate population density and urbanization intensity.

5. Conclusions

This study comprehensively investigated the ES tradeoffs (supply–supply tradeoff, supply–demand tradeoff, and demand–demand tradeoff) in the urban agglomeration of the YRD by mapping the bundles of ES considering both supply and demand. Based on several statistical techniques, we found that the spatial distributions of ES supply and demand were highly heterogeneous with strong spatial autocorrelations. Significant correlations exist among ES in terms of supply–supply, supply–demand, and supply–demand. Four ES supply–demand bundle types were identified with distinct land use, urban intensity, and climatic characteristics. The identified ES supply–demand bundles can provide scientific evidence for the zoning of main functional areas in the Yangtze River Delta. Our results also suggest that land sharing is a more appropriate approach for the sustainable development of the Yangtze River Delta considering the balance of ES supply and demand. Future research could further help develop balanced strategies on how to improve ES synergies while reduce tradeoffs by considering ES supply and demand.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11091558/s1, Table S1. Key parameters of each LUCC class for the InVEST urban cooling model. Table S2. The CN value for each LULC type. Table S3. The components, factors, and data sources for calculating outdoor recreation potential. Table S4. Cross-tabulation matrix was used to determine outdoor recreation demand values.

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References

1. Haase, D.; Schwarz, N.; Strohbach, M.; Kroll, F.; Seppelt, R. Synergies, Trade-offs, and Losses of Ecosystem Services in Urban Regions: An Integrated Multiscale Framework Applied to the Leipzig-Halle Region, Germany. *Ecol. Soc.* **2012**, *17*, 22. [CrossRef]
2. Fang, X.; Zhou, B.; Tu, X.; Ma, Q.; Wu, J. "What Kind of a Science is Sustainability Science?" An Evidence-Based Reexamination. *Sustainability* **2018**, *10*, 1478. [CrossRef]
3. Bennett, E.M.; Peterson, G.D.; Gordon, L.J. Understanding relationships among multiple ecosystem services. *Ecol. Lett.* **2009**, *12*, 1394–1404. [CrossRef]
4. *Ecosystems and Human Well-Being: Current State and Trends*; 2005. Available online: https://islandpress.org/books/ecosystems-and-human-well-being-current-state-and-trends (accessed on 10 August 2022).
5. Haines-Young, R.; Potschin, M. The links between biodiversity, ecosystem services and human well-being. In *Ecosystem Ecology: A New Synthesis*; Cambridge University Press: Cambridge, UK, 2010.
6. Wolff, S.; Schulp, C.J.E.; Verburg, P.H. Mapping ecosystem services demand: A review of current research and future perspectives. *Ecol. Indic.* **2015**, *55*, 159–171. [CrossRef]
7. Rodríguez, J.P.; Beard, T.D., Jr.; Bennett, E.M.; Cumming, G.S. Trade-offs across Space, Time, and Ecosystem Services. *Ecol. Soc.* **2005**, *11*, 709–723. [CrossRef]
8. Mouchet, M.A.; Lamarque, P.; Martín-López, B.; Crouzat, E.; Gos, P.; Byczek, C.; Lavorel, S. An interdisciplinary methodological guide for quantifying associations between ecosystem services. *Glob. Environ. Chang.* **2014**, *28*, 298–308. [CrossRef]
9. Raudsepp-Hearne, C.; Peterson, G.D.; Bennett, E.M. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 5242–5247. [CrossRef]
10. Howe, C.; Suich, H.; Vira, B.; Mace, G.M. Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Glob. Environ. Chang.-Hum. Policy Dimens.* **2014**, *28*, 263–275. [CrossRef]
11. Renard, D.; Rhemtulla, J.M.; Bennett, E.M. Historical dynamics in ecosystem service bundles. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 13411–13416. [CrossRef]
12. Zhao, M.; Peng, J.; Liu, Y.; Li, T.; Wang, Y. Mapping Watershed-Level Ecosystem Service Bundles in the Pearl River Delta, China. *Ecol. Econ.* **2018**, *152*, 106–117. [CrossRef]
13. Haberman, D.; Bennett, E.M. Ecosystem service bundles in global hinterlands. *Environ. Res. Lett.* **2019**, *14*, 084005. [CrossRef]
14. Zoderer, B.M.; Tasser, E.; Carver, S.; Tappeiner, U. Stakeholder perspectives on ecosystem service supply and ecosystem service demand bundles. *Ecosyst. Serv.* **2019**, *37*, 100938. [CrossRef]
15. Li, K.; Hou, Y.; Andersen, P.S.; Xin, R.; Rong, Y.; Skov-Petersen, H. An ecological perspective for understanding regional integration based on ecosystem service budgets, bundles, and flows: A case study of the Jinan metropolitan area in China. *J. Environ. Manag.* **2022**, *305*, 114371. [CrossRef]
16. Baro, F.; Gomez-Baggethun, E.; Haase, D. Ecosystem service bundles along the urban-rural gradient: Insights for landscape planning and management. *Ecosyst. Serv.* **2017**, *24*, 147–159. [CrossRef]

17. Quintas-Soriano, C.; García-Llorente, M.; Norström, A.; Meacham, M.; Peterson, G.; Castro, A.J. Integrating supply and demand in ecosystem service bundles characterization across Mediterranean transformed landscapes. *Landsc. Ecol.* **2019**, *34*, 1619–1633. [CrossRef]
18. Wu, J.G. Urban ecology and sustainability: The state-of-the-science and future directions. *Landsc. Urban Plan.* **2014**, *125*, 209–221. [CrossRef]
19. Xu, X.B.; Yang, G.S.; Tan, Y.; Liu, J.P.; Hu, H.Z. Ecosystem services trade-offs and determinants in China's Yangtze River Economic Belt from 2000 to 2015. *Sci. Total Environ.* **2018**, *634*, 1601–1614. [CrossRef]
20. Chen, D.S.; Jiang, P.H.; Li, M.C. Assessing potential ecosystem service dynamics driven by urbanization in the Yangtze River Economic Belt, China. *J. Environ. Manag.* **2021**, *292*, 16. [CrossRef]
21. Tao, Y.; Wang, H.N.; Ou, W.X.; Guo, J. A land-cover-based approach to assessing ecosystem services supply and demand dynamics in the rapidly urbanizing Yangtze River Delta region. *Land Use Pol.* **2018**, *72*, 250–258. [CrossRef]
22. Chen, W.X.; Chi, G.Q.; Li, J.F. Ecosystem Services and Their Driving Forces in the Middle Reaches of the Yangtze River Urban Agglomerations, China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 3717. [CrossRef]
23. Zhang, D.; Wang, X.R.; Qu, L.P.; Li, S.C.; Lin, Y.P.; Yao, R.; Zhou, X.; Li, J.Y. Land use/cover predictions incorporating ecological security for the Yangtze River Delta region, China. *Ecol. Indic.* **2020**, *119*, 11. [CrossRef]
24. Zawadzka, J.E.; Harris, J.A.; Corstanje, R. Assessment of heat mitigation capacity of urban greenspaces with the use of InVEST urban cooling model, verified with day-time land surface temperature data. *Landsc. Urban Plan.* **2021**, *214*, 104163. [CrossRef]
25. Pistocchi, A.; Zulian, G.; Vizcaino, P.; Marinov, D. *Multimedia Assessment of Pollutant Pathways in the Environment, European Scale Model (MAPPE-Europe)*; Office for Official Publications of the European Communities: Luxembourg, 2010.
26. Hamel, P.; Guerry, A.D.; Polasky, S.; Han, B.; Douglass, J.A.; Hamann, M.; Janke, B.; Kuiper, J.J.; Levrel, H.; Liu, H.; et al. Mapping the benefits of nature in cities with the InVEST software. *Npj Urban Sustain.* **2021**, *1*, 1–9. [CrossRef]
27. Baro, F.; Palomo, I.; Zulian, G.; Vizcaino, P.; Haase, D.; Gomez-Baggethun, E. Mapping ecosystem service capacity, flow and demand for landscape and urban planning: A case study in the Barcelona metropolitan region. *Land Use Pol.* **2016**, *57*, 405–417. [CrossRef]
28. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56*; FAO: Rome, Italy, 1998; Volume 300, p. D05109.
29. Taha, H.; Akbari, H.; Rosenfeld, A.; Huang, J. Residential cooling loads and the urban heat island—The effects of albedo. *Build. Environ.* **1988**, *23*, 271–283. [CrossRef]
30. Oke, T.R.; Stewart, I.D. Local Climate Zones for Urban Temperature Studies. *Bull. Am. Meteorol. Soc.* **2012**, *93*, 1879–1900. [CrossRef]
31. Cronshey, R. *Urban Hydrology for Small Watersheds*; 1986. Available online: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf (accessed on 10 August 2022).
32. Bing, Z.H.; Qiu, Y.S.; Huang, H.P.; Chen, T.Z.; Zhong, W.; Jiang, H. Spatial distribution of cultural ecosystem services demand and supply in urban and suburban areas: A case study from Shanghai, China. *Ecol. Indic.* **2021**, *127*, 11. [CrossRef]
33. Cao, Y.; Cao, Y.; Li, G.; Tian, Y.; Fang, X.; Li, Y.; Tan, Y. Linking ecosystem services trade-offs, bundles and hotspot identification with cropland management in the coastal Hangzhou Bay area of China. *Land Use Pol.* **2020**, *97*, 104689. [CrossRef]
34. Li, J.; Jiang, H.; Bai, Y.; Alatalo, J.M.; Li, X.; Jiang, H.; Liu, G.; Xu, J. Indicators for spatial–temporal comparisons of ecosystem service status between regions: A case study of the Taihu River Basin, China. *Ecol. Indic.* **2016**, *60*, 1008–1016. [CrossRef]
35. Power, A.G. Ecosystem services and agriculture: Tradeoffs and synergies. *Philos. Trans. R. Soc. B-Biol. Sci.* **2010**, *365*, 2959–2971. [CrossRef]
36. Qiu, J.; Turner, M.G. Spatial interactions among ecosystem services in an urbanizing agricultural watershed. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 12149–12154. [CrossRef]
37. Burkhard, B.; Kroll, F.; Nedkov, S.; Müller, F. Mapping ecosystem service supply, demand and budgets. *Ecol. Indic.* **2012**, *21*, 17–29. [CrossRef]
38. Baro, F.; Haase, D.; Gomez-Baggethun, E.; Frantzeskaki, N. Mismatches between ecosystem services supply and demand in urban areas: A quantitative assessment in five European cities. *Ecol. Indic.* **2015**, *55*, 146–158. [CrossRef]
39. Wu, X.; Liu, S.; Zhao, S.; Hou, X.; Xu, J.; Dong, S.; Liu, G. Quantification and driving force analysis of ecosystem services supply, demand and balance in China. *Sci. Total Environ.* **2019**, *652*, 1375–1386. [CrossRef] [PubMed]
40. Fang, X.; Wu, J.; He, C. Assessing human-environment system sustainability based on Regional Safe and Just Operating Space: The case of the Inner Mongolia Grassland. *Environ. Sci. Policy* **2021**, *116*, 276–286. [CrossRef]
41. Fang, X.; Wu, J. Causes of overgrazing in Inner Mongolian grasslands: Searching for deep leverage points of intervention. *Ecol. Soc.* **2022**, *27*, 8. [CrossRef]
42. Larondelle, N.; Lauf, S. Balancing demand and supply of multiple urban ecosystem services on different spatial scales. *Ecosyst. Serv.* **2016**, *22*, 18–31. [CrossRef]
43. Lin, B.B.; Fuller, R.A.; Thompson, D. FORUM: Sharing or sparing? How should we grow the world's cities? *J. Appl. Ecol.* **2013**, *50*, 1161–1168. [CrossRef]
44. Karimi, J.D.; Corstanje, R.; Harris, J.A. Bundling ecosystem services at a high resolution in the UK: Trade-offs and synergies in urban landscapes. *Landsc. Ecol.* **2021**, *36*, 1817–1835. [CrossRef]