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# Spatiotemporal Patterning and Matching of Ecosystem Services' Supply and Demand in Changchun, China

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**Abstract:** The process of urbanization has deepened the contradiction between ecosystem services' supply and demand, resulting in a significant risk to ecological security. Thus, it is imperative to conduct an analysis of the correlation between ecosystem services' supply and demand to achieve sustainable urban growth. This study evaluated the supply, demand, coordination index, and matching types of ecosystem services' supply and demand in 2000, 2010, and 2020 based on multisource data in Changchun City. The results showed that ecosystem services' supply decreased overall, while their demand continued to increase from 2000 to 2020, together with their spatial heterogeneity. The regions characterized by a low supply of and high demand for ecosystem services mostly encompassed central urban regions that have undergone a substantial level of socioeconomic advancement. Conversely, the regions characterized by a high supply and low demand were primarily hilly regions with a sparse population that were situated at higher altitudes. There has been slight incoordination between ecosystem services' supply and demand in Changchun. In the future, it is imperative for sustainable urban development strategies to protect cultivated and ecological lands, extensively enhance the benefits of the lands, and facilitate the coordinated development of cities, agriculture, and ecology.

**Keywords:** ecosystem services; supply and demand; spatiotemporal patterns; supply–demand matching

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## 1. Introduction

In the past few decades, the accelerated progress of socioeconomic development and urbanization have caused disturbance and damage to regional ecosystems, resulting in a considerable decrease in the capacity of ecosystems to deliver services to humans. Simultaneously, population explosion has continuously increased the demand for ecosystem products. This has resulted in an imbalance of ecosystems and a series of ecological problems, including natural environmental pollution, ecosystem degradation, and a sharp decline in biodiversity, which have gravely affected human wellbeing [1]. Therefore, it is imperative to analyze the correlation between ecosystem services' supply and demand in order to attain sustainable urban development and improve human wellbeing.

Ecosystem services (ESs), which serve as an essential link connecting the natural environment and human society, refer to a range of benefits that humans receive from ecosystems [2–4]. From the viewpoint of ecosystem service production and use, they can be divided into two aspects: ecosystem services' supply (ESS) and ecosystem services' demand (ESD). Research on ecosystem services' supply and demand (ESSD) has gained significant attention in the fields of ecological compensation, urban planning, ecological management, and others [5,6]. The current study primarily focuses on a few aspects [7]. Firstly, the theoretical research on ecosystem services' supply and demand has made significant progress in regard to spatial quantification methods [8,9], formation mechanisms and cost effects [10,11], and cartographic representations [12,13]. Secondly, to provide more systematic implications, researchers have explored the spatiotemporal features of the correlation between ecosystem services' supply and demand at multiple scales, including global [14], national [15], urban agglomeration [16,17], and river basin [18,19]. These studies have found that ecosystem services' supply and demand present significant spatial heterogeneity, with mismatches concentrated in highly urbanized areas [20–22]. The third aspect is incorporating ecosystem services' supply and demand into ecological management practices, including ecological restoration zoning [23,24], ecological security patterns [25], ecological compensation policy [26], and risk assessment [27].

In terms of methodology, diverse methods have been applied in research on ecosystem services' supply, such as public participation [28], value evaluation [29], empirical statistical modeling [19,30], and ecological modeling [31]. There exist two primary approaches for estimating ecosystem services' demand. To begin with, from the perspective of cognition, scholars have evaluated ecosystem services' demand by using questionnaires [7], expert experience methods, and evaluation matrices [32]. Secondly, ecosystem services' demand is generally quantified by using socioeconomic indicators, including land use intensity, population density, and gross domestic product (GDP) [22,33]. Methods based on a cognitive perspective are subjective and cannot effectively demonstrate spatial heterogeneity. The substitution method based on actual objective indicators is applied widely, yet no evaluation standard is available [34]. Therefore, it is imperative to thoroughly incorporate local characteristics and regional differences when assessing ecosystem services' supply and demand. Furthermore, the most suitable evaluation method should be selected based on the different research scales and problems to be solved. To assess ecosystem services' supply and demand mismatches, the coordination degree [35], supply–demand ratio [30], and budget [27] can be used to assess mismatches in quantifiable terms, while the Getis–Ord Gi* statistic and the bivariate Moran's Index [36] can be employed to achieve spatial visualization. The identification of factors contributing to mismatches can be determined through nonspatial regression methods, including stepwise linear regression, redundancy analysis, structural equation modeling, and random forest [37].

Nevertheless, few studies have been conducted on ecosystem services' supply and demand in the northeast of China. Changchun, situated in the heart of the Northeast Asian Economic Circle, serves as the capital of Jilin Province and holds a significant status as a key industrial base within China. Changchun City has experienced unprecedented urbanization and industrialization in recent decades, driven by the implementation of a policy aimed at revitalizing the historical industrial bases in the northeast of China. Rapid urbanization has had a profound effect on its land use structure and deepened the contradiction between its ecosystem services' supply and demand, which has led to a threat to its ecological security. Therefore, with a focus on the interconnection between the ecosystem and the economic system, this study analyzed the spatiotemporal dynamics, matching types, and coordination of ecosystem services' supply and demand in Changchun City from 2000 to 2020. Subsequently, we proposed corresponding governance strategies based on these spatial distribution differences. Our aim is to offer a theoretical framework that may support the development of scientific policies and the implementation of integrative ecological restoration plans.

## 2. Materials and Methods

### 2.1. Study Area

Changchun serves as the capital of Jilin Province, which is situated within the geographical coordinates of 43°05′ N–45°15′ N and 124°18′ E–127°05′ E in the mid-latitude region of the Northern Hemisphere. Changchun has a temperate continental monsoon climate [38]. It is dry and cold during the winter, while it receives more precipitation and has higher temperatures during the summer. The average annual temperature and the average annual precipitation are recorded to be 4.8 °C and 522–615 mm, respectively. The temperature increases from north to south, and the precipitation level decreases from east to west. The terrain exhibits an elevation gradient, with higher elevations in the east and lower elevations in the west, and is mainly composed of platforms and plains. The region exhibits a flat terrain, characterized by an elevation ranging from 250 to 350 m above sea level, which is conducive for agricultural activities. The largest land area is occupied by cultivated land, followed by construction land and forest. Changchun covers an area of $2.06 \times 10^4$ km$^2$, and it holds significant prominence as an industrial base situated in the northeastern region of China, with a total population of $9.07 \times 10^6$. In recent decades, the speed of urbanization and industrialization in Changchun City has experienced significant acceleration, resulting in a misadjustment between the supply of and demand for ecosystem services (Figure 1).

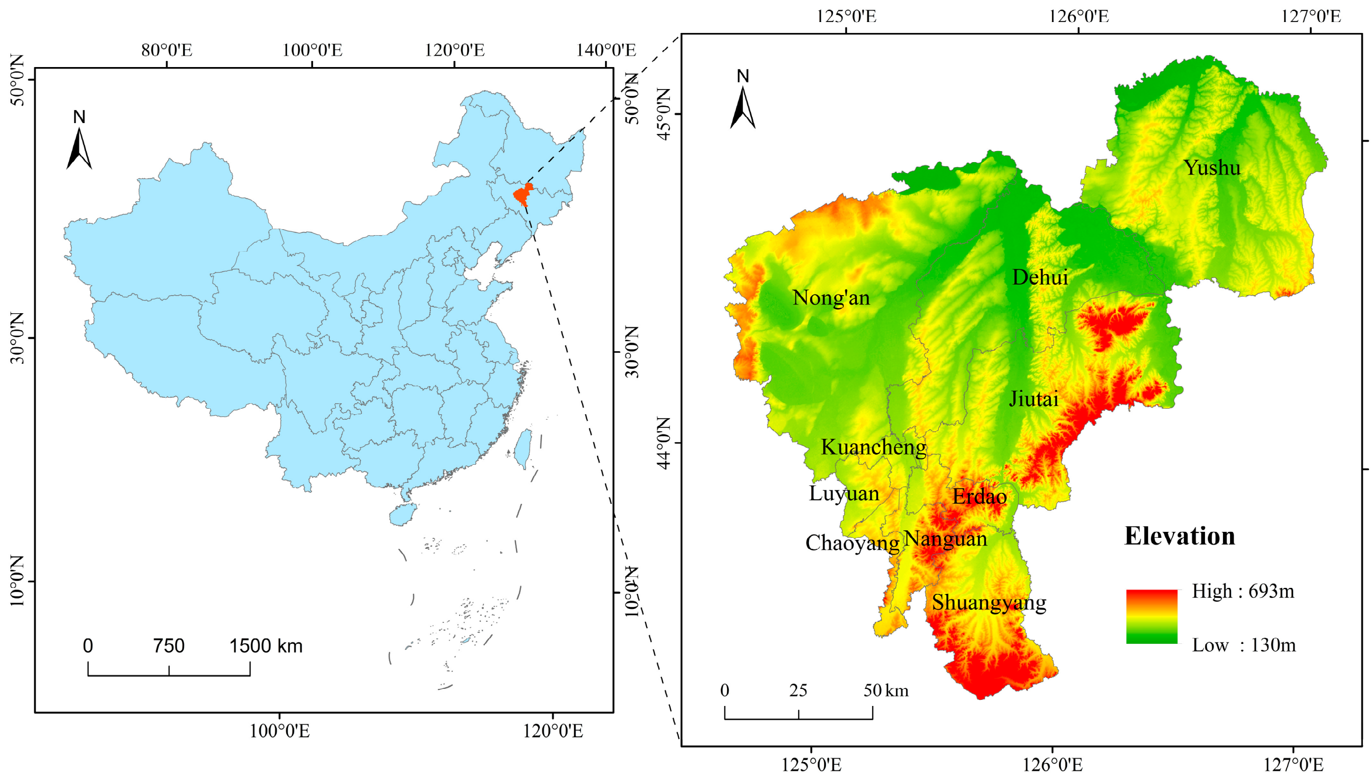



**Figure 1.** Diagram of the study area.

## *2.2. Data Sources*

In this research study, multisource data were applied, as indicated in Table 1. The land use dataset encompasses six different types of land use: cultivated land, forest, grassland, water bodies, construction land, and unused land. Most data were acquired from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (RESDCCAS) (http://www.resdc.cn, accessed on 20 March 2023), including the land use, DEM, GDP spatial distribution, population spatial distribution, and nighttime light brightness data. In view of the unavailability of population and GDP data for 2020, they were replaced by the population and GDP data of 2019. The monthly potential evapotranspiration and monthly precipitation data were drawn from the National Earth System Science Data Center, National Science and Technology Infrastructure of China (NESSDC) (http://www.geodata.cn, accessed on 20 May 2023). Soil data were obtained from the Harmonized World Soil Database (HWSD). We resampled all raster data into data with a pixel resolution of 30 m $\times$ 30 m via the WGS_1984 coordinate system based on ArcGIS 10.8.

**Table 1.** Data sources.

| Data Name | Year of Data | Data Source |
|---|---|---|
| Land use data | 2000/2010/2020 | RESDCCAS (https://www.resdc.cn/, accessed on 20 March 2023) [39] |
| DEM | – | RESDCCAS (https://www.resdc.cn/, accessed on 20 March 2023) |
| Watershed | – | RESDCCAS (https://www.resdc.cn/, accessed on 20 March 2023) |
| GDP | 2000/2010/2019 | RESDCCAS (https://www.resdc.cn/, accessed on 20 March 2023) |
| Population | 2000/2010/2019 | RESDCCAS (https://www.resdc.cn/, accessed on 20 March 2023) |
| Nighttime light | 2000/2010/2020 | RESDCCAS (https://www.resdc.cn/, accessed on 20 March 2023) |
| Monthly potential evapotranspiration | 2000/2010/2020 | NESSDC (http://www.geodata.cn, accessed on 20 May 2023) [40] |
| Monthly precipitation | 2000/2010/2020 | NESSDC (http://www.geodata.cn, accessed on 20 May 2023) |
| Soil | – | HWSD |

### *2.3. Research Methods*

#### 2.3.1. Ecosystem Services' Supply Measurement

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model was created by Stanford University, the Nature Conservancy (TNC), and the World Wide Fund for Nature (WWF), and it aims to quantify and evaluate ecosystem services under various land use scenarios [38]. It has been extensively used to estimate ecosystem services due to its inherent benefits such as simple parameters and visualized results. Based on the actual situation and data accessibility, we chose four ecosystem services: water yield, carbon storage, soil conservation, and habitat quality. The calculations are expressed in Table 2. According to the existing research on Changchun [38,41], we obtained the parameters involved in the models. Then, we normalized the results and summed them with equal weights to calculate the total supply of ecosystem services.

**Table 2.** Calculation of ecosystem services' supply based on the InVEST model.

| Ecosystem Service | Calculation Formula | Explanation | Data Required in the Model |
|---|---|---|---|
| Water yield | $Y_x = \left(1 - \frac{AET_x}{P_X}\right) \times P_x$<br>$\frac{AET_x}{P_X} = \frac{1+\omega_x R_x}{1+\omega_x R_x + \frac{1}{R_x}}$<br>$\omega_x = Z\frac{AWC_x}{P_X} + 1.25$<br>$AWC_x = \min(rest.layer.depth, root.depth) \times PAWC$<br>$R_x = \frac{K_x ET_{0x}}{P_X}$ | The variable $Y_x$ denotes the water yield of grid cell $x$. $AET_x$ denotes the actual yearly evapotranspiration of grid cell $x$, whereas $P_x$ indicates the average annual precipitation of grid cell $x$. $R_x$ denotes the Budyko aridity index of grid cell $x$, whereas $\omega_x$ denotes the nonphysical parameter of natural climate soil properties. $AWC_x$ represents the effective soil moisture content, and it was calculated by multiplying the plant available water capacity (PAWC) and the minimum of root-restricting layer depth and vegetation rooting depth. $ET0_x$ denotes the reference vegetation evapotranspiration of grid cell $x$, and $K_x$ denotes the vegetation evapotranspiration coefficient of land use type in grid cell $x$. $Z$ denotes an empirical constant. | Land use map of 2000/2010/2020 (raster); annual potential evapotranspiration of 2000/2010/2020 (raster); annual precipitation of 2000/2010/2020 (raster); PAWC (raster) (calculated from soil data) [41]; restricting layer depth (raster) (calculated from soil data); watershed (vector); biophysical table (csv) (columns: lucode, lulc_veg, root_depth, and kc) [41]; Z parameter [41]. |
| Carbon storage | $C_{x\_total} = C_{x\_above} + C_{x\_below} + C_{x\_soil} + C_{x\_dead}$ | $C_{x\_total}$ represents the total carbon storage of grid cell $x$; $C_{x\_above}$ represents the aboveground vegetation carbon storage of grid cell $x$; $C_{x\_below}$ represents the belowground vegetation carbon storage of grid cell $x$; $C_{x\_soil}$ represents the soil carbon storage of grid cell $x$; and $C_{x\_dead}$ denotes the carbon storage associated with dead organic matter of grid cell $x$. | Land use map of 2000/2010/2020 (raster); carbon pools (csv) (columns: lucode, c_above, c_below, c_soil, and c_dead) [38]. |

**Table 2.** *Cont.*

| Ecosystem Service | Calculation Formula | Explanation | Data Required in the Model |
|---|---|---|---|
| Soil conservation | $RKLS_x = R_x \times K_x \times LS_x$ <br> $USLE_x = R_x \times K_x \times LS_x \times C_x \times P_x$ <br> $SEDRET_x = RKLS_x - USLE_x$ | $SEDRET_x$ represents the soil retention; $RKLS_x$ represents the potential soil erosion; $USLE_x$ represents the actual soil erosion; $R_x$ denotes the rainfall erosivity factor; $K_x$ denotes the soil erodibility factor; $LS_x$ denotes the slope length factor; $C_x$ denotes the vegetation cover management factor; and $P_x$ denotes the soil and water conservation measure factor. | Land use map of 2000/2010/2020 (raster); digital elevation model (raster); erosivity of 2000/2010/2020 (raster) (calculated from monthly precipitation data) [41]; soil erodibility (calculated from soil data) [41]; watersheds (vector); biophysical table (csv) (columns: lucode, usle_c, and usle_p) [41]. |
| Habitat quality | $Q_{xj} = H_j\left[1 - \left(\frac{D_{xj}^2}{D_{xj}^2 + K^2}\right)\right]$ <br> $D_{xj} = \sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\omega_r / \sum_{r=1}^{R}\omega_r\right) r_y i_{rxy} \beta_x S_{jr}$ | $Q_{xj}$ denotes the habitat quality of grid cell $x$ inside habitat type $j$; $H_j$ denotes the suitability of habitat type $j$; ${D^2}_{xj}$ denotes the total threat level of grid cell $x$ in habitat type $j$; $K^2$ denotes the half-saturation constant; $R$ denotes the number of threat sources; $Y_r$ denotes the grid number of threat sources; $\omega_r$ denotes the weight of the threat source $r$; $r_y$ denotes the stress value of grid cell $y$; $i_{rxy}$ denotes the stress level of $r_y$ on grid cell $x$; $\beta_x$ denotes the accessibility of the threat source to grid cell $x$; and $S_{jr}$ denotes the sensitivity of habitat type $j$ to threat source $r$. | Land use map of 2000/2010/2020 (raster); threat data of 2000/2010/2020 (raster) (extracted from land use data); threats table (csv) (columns: threat, max_dist, weight, decay, and cur_path) [41]; and sensitivity table (csv) (columns: lulc, habitat, and threat ratio) [41]. |

### 2.3.2. Ecosystem Services' Demand Measurement

At present, scholars have presented three main understandings of ecosystem services' demand: (1) Burkhard et al. [42] believe that ecosystem services' demand is the total amount of ecosystem products and services used or consumed by humans within a certain period of time. (2) Schreiter et al. [43] believe that ecosystem services' demand is an expression of individual human preferences for specific attributes of ecosystem services, such as biophysical characteristics, available locations and times, and associated opportunity costs. In other words, ecosystem services' demand expresses human preferences for enjoying ecosystem services, which may exceed the products and services currently consumed or used by humans. (3) Villamagna et al. [44] comprehensively investigated the consumption and preferential demand for ecosystem services in human basic life. They came to the conclusion that ecosystem services' demand is the quantity of ecosystem services consumed (available) or desired by human society.

This study adopted the third understanding of ecosystem services' demand, which includes both available (consumed) products or services and desired ones. With reference to previous studies and based on the actual situation and data accessibility in Changchun City, we selected four socioeconomic indicators—land use intensity, population, GDP, and nighttime light brightness—to comprehensively represent human demand. In accordance with Li [23], we replaced the fraction of construction land by land use intensity and divided it into four levels: 1 (unused land), 2 (forest, grassland, and water body), 3 (cultivated land), and 4 (construction land). Due to the great differences in the spatial distributions of different data sets, we employed the natural logarithm to eliminate local violent fluctuations. The formula is expressed as the following:

$$ESD = R + \lg(P+1) + \lg(G+1) + \lg(N+1) \quad (1)$$

$$R = 100 \times \sum_{i=1}^{n} (H_i \times M_i) \quad (2)$$

where *ESD* denotes the ecosystem services' demand; *R* represents the land use intensity; *P* represents the population intensity; *G* represents the GDP data; *N* represents the nighttime light brightness; $H_i$ is the land use intensity of level *i* (*i* = 1, 2, 3, 4); and $M_i$ represents the proportion of *i*-level land use types.

2.3.3. Ecosystem Services' Supply and Demand Matching

We standardized the ecosystem services' supply and demand using a z-score to analyze their spatial matching relationship. Then, we constructed a coordinate system wherein the x-axis was the standardized ecosystem services' supply and the y-axis was the standardized ecosystem services' demand. According to the distribution in the coordinate system, the supply–demand matching was divided into four types: high supply–high demand (x > 0, y > 0); low supply–high demand (x < 0, y > 0); low supply–low demand (x < 0, y < 0); and high supply–low demand (x > 0, y < 0). The formula for the z-score standardization is the following:

$$x = \frac{x_i - \overline{x}}{s} \quad (3)$$

where *x* is the standardized ecosystem services' supply or demand; $x_i$ denotes the supply or demand of grid cell *i*; $\overline{x}$ denotes the average value of the whole study area; and *S* denotes the standard deviation.

2.3.4. Ecosystem Services' Supply and Demand Coordination

A coordination index can reflect the coupling correlation between ecosystem services' supply and demand, and the degree of interactive development between the two. To reduce the dimensional impact, range standardization was first performed in the calculation. The calculation formulae for the coordination index are the following:

$$D = \sqrt{C \times T} \quad (4)$$

$$C = \sqrt{\frac{P_s \times P_d}{[(P_s + P_d)/2]^2}} \quad (5)$$

$$T = \alpha P_s + \beta P_d \quad (6)$$

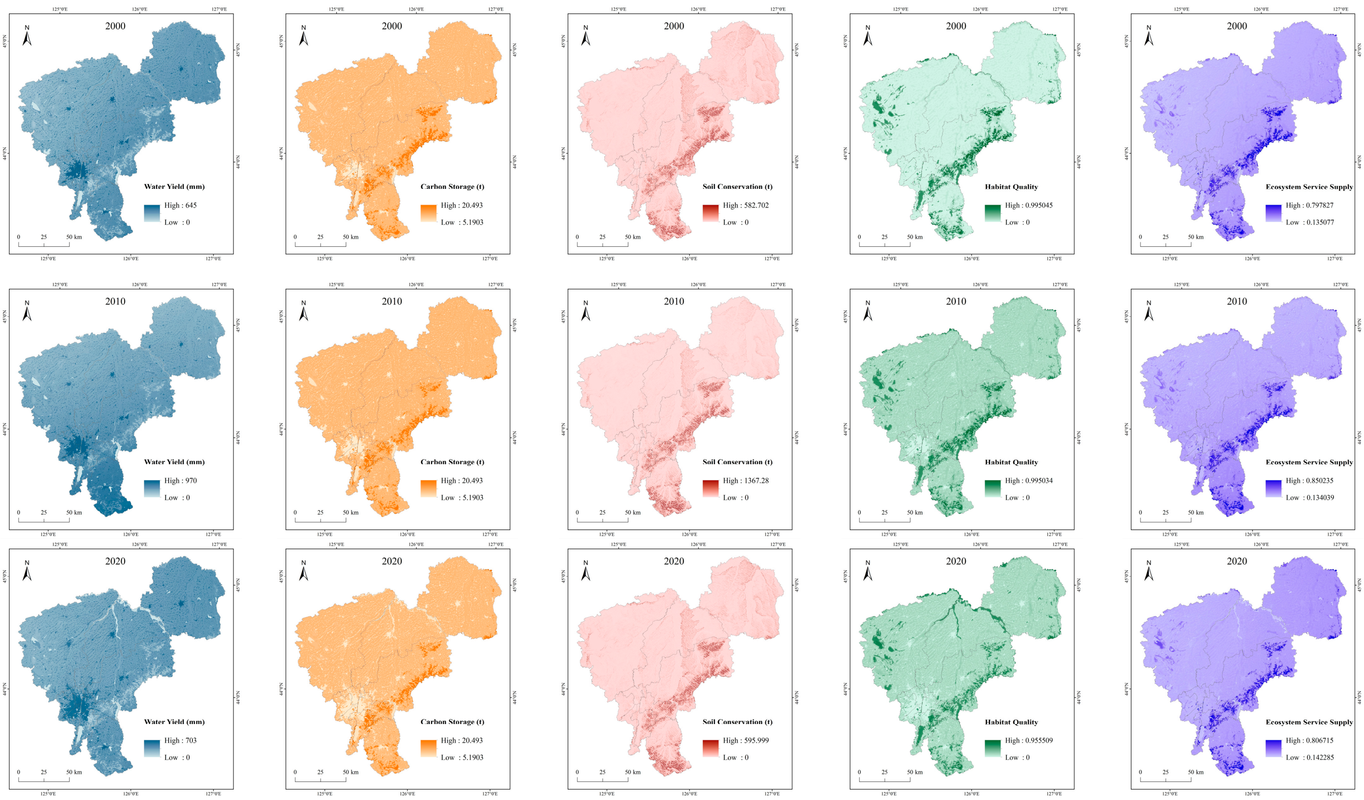
where *D* is the coordination index. Its value ranged from 0 to 1, and the closer the value to 1, the higher the degree of coordination. *C* denotes the coupling degree and *T* denotes the comprehensive index. $P_s$ denotes the normalized ecosystem services' supply; $P_d$ denotes the normalized ecosystem services' demand; and $\alpha$ and $\beta$ denote the weight coefficients.

We set the ecosystem services' supply and demand to be equally important in the coordination analysis: $\alpha = \beta = 0.5$. The results were determined by using the natural breakpoint method and divided into five types: high misadjustment, mid-misadjustment, basic coordination, mid-coordination, and high coordination.

## 3. Results

*3.1. Spatiotemporal Patterns of Ecosystem Services' Supply*

The spatial distribution maps of the ecosystem services' supply in Changchun City were created by running four modules in the InVEST model: annual water yield, carbon storage and sequestration, sediment delivery ratio, and habitat quality (Figure 2).



(**a**) (**b**) (**c**) (**d**) (**e**)

**Figure 2.** Spatiotemporal patterns of ecosystem services' supply in Changchun. (**a**) Water yield; (**b**) carbon storage; (**c**) soil conservation; (**d**) habitat quality; (**e**) ecosystem services' supply.

Water yield reflects the water production function of an ecosystem and is an important indicator for measuring water source conservation, which has tremendous importance in the effective utilization of regional water resources. The water yields of Changchun City in 2000, 2010, and 2020 were $5.41 \times 10^9$ m$^3$, $8.23 \times 10^9$ m$^3$, and $6.78 \times 10^9$ m$^3$, respectively. These figures indicate a pattern of initial growth, followed by a subsequent decline, resulting in an overall increase of $1.37 \times 10^9$ m$^3$ in the past 20 years. The growth rate was relatively fast from 2000 to 2010, with an increase of $2.82 \times 10^9$ m$^3$. From 2010 to 2020, the water yield reduced by $1.45 \times 10^9$ m$^3$. In 2000 and 2020, the water yield in Changchun City was relatively low, with an average of 262.32 mm and 328.76 mm, respectively. In 2010, the average water yield was 399.45 mm, which showed a significant increase. In terms of spatial distribution, it could be observed that the water yield in the eastern hilly areas of Changchun City was relatively low, while it was relatively high in the built-up areas of the city and its surrounding counties (Figure 2a). In the period from 2000 to 2020, the water yield in the southwest part of Changchun City, as well as in Shuangyang District, showed significant changes. An ecosystem's water production capacity is primarily determined by its precipitation and vegetation evapotranspiration. The precipitation of Changchun City in 2000 and 2020 showed characteristically higher levels in the eastern region and comparatively lower levels in the west. However, the precipitation in 2010 was higher than that in the other two years, exhibiting a decline in a northward direction. Thus, the water yield in 2010 was higher and had a different spatial pattern.

Carbon storage, which has significant importance in the efforts to mitigate global climate change, is a direct manifestation of terrestrial ecosystem productivity [1]. Over the course of the previous two decades, the carbon storage of the ecosystem in Changchun continued to decline from $2.23 \times 10^8$ t in 2000 to $2.22 \times 10^8$ t in 2010 and $2.16 \times 10^8$ t in 2020, exhibiting an overall reduction of $7.02 \times 10^6$ t. The average carbon density values were 1.08 t/km$^2$, 1.07 t/km$^2$, and 1.05 t/km$^2$, respectively, showing a downward trend. In terms of spatial distribution, it was observed that the distribution of carbon storage had a high value in the southeastern region. Conversely, the central area had comparatively lower levels of carbon storage (Figure 2b). The forest exhibited a notable high carbon storage, as shown by a carbon density of 2.28 $t/km^2$. Compared to the forest, the carbon density of cultivated land was lower; however, due to its large area, it had more carbon storage. Areas with a low carbon density were found to be mostly situated in construction land, water bodies, and unused land. Accompanying urban development, construction land continued to encroach on other types of land, leading to a notable decline in carbon storage from 2000 to 2020.

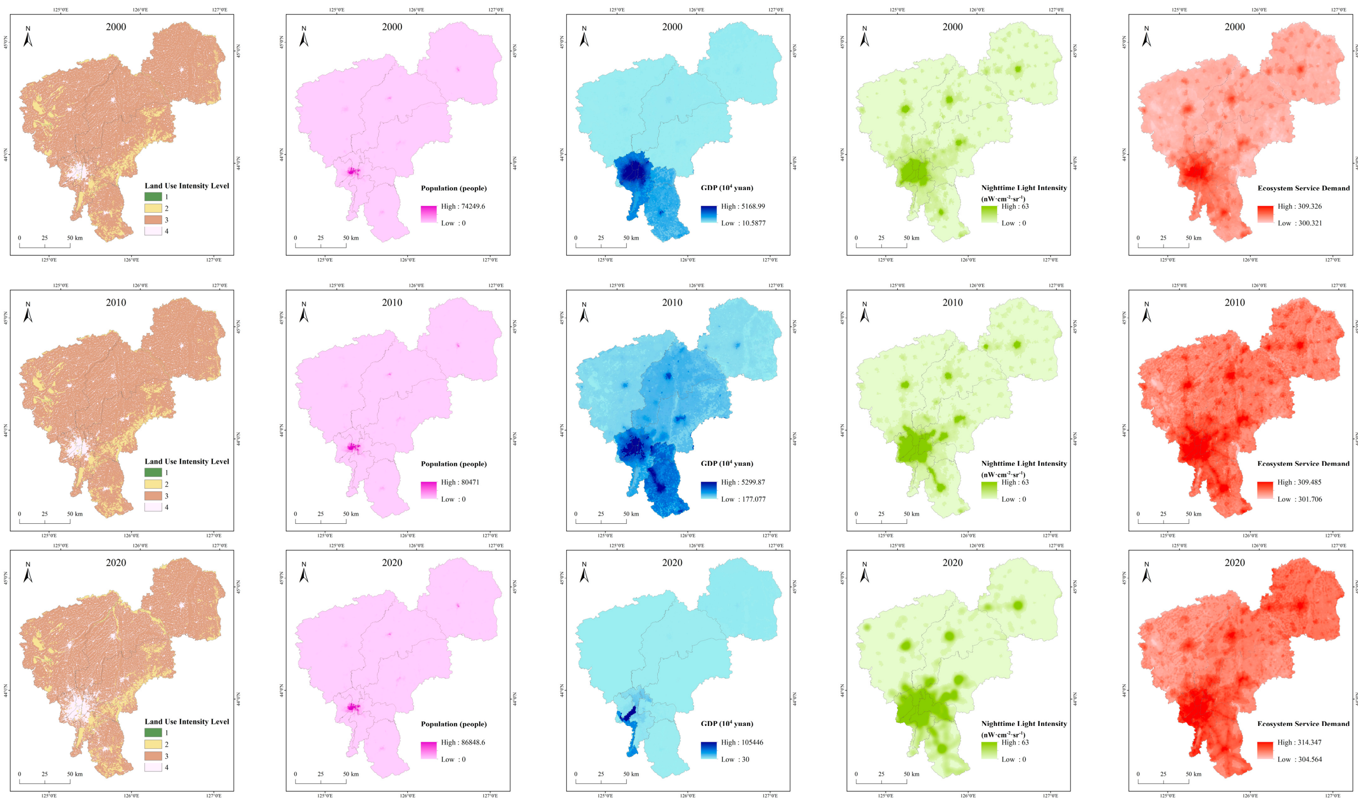
Soil conservation reflects an ecosystem's capacity to mitigate soil erosion and maintain sediments and is an important functional indicator of ecosystem regulation services. The total soil conservation values in Changchun City in 2000, 2010, and 2020 were, respectively, $5.13 \times 10^7$ t, $8.22 \times 10^7$ t, and $5.16 \times 10^7$ t. Between the years 2000 and 2010, soil conservation showed a growth trend, with a total increase of $3.09 \times 10^7$ t and an average increase of 0.15 $t/km^2$. In the past decade, soil conservation decreased by $3.06 \times 10^7$ t, with an average decrease from 0.40 $t/km^2$ to 0.25 $t/km^2$. Soil conservation in Changchun increased progressively from the northwest to southeast (Figure 2c). The regions with a high value of soil conservation were mostly concentrated in Jiutai, Shuangyang, and Nanguan. These areas are mainly mountainous and have extensive forest coverage and a strong ability for soil conservation.

Habitat quality refers to the environmental quality of regional ecosystems, playing a crucial role in facilitating ecological services such as material circulation, energy flow, and information transmission. It is an important indicator that reflects the stability, balance, and biodiversity of ecosystems. Rapid urbanization, resulting in habitat fragmentation and degradation, is considered the biggest driving force behind the decline in habitat quality. The mean habitat quality of Changchun City in 2000, 2010, and 2020 was recorded as 0.2133, 0.2118, and 0.1958, respectively, showing a slight decrease overall. The regional distribution of habitat quality exhibited a distinct pattern, characterized by being higher in the southeastern region and lower in the northwestern region. (Figure 2d). The areas with high habitat quality were mostly located around the eastern Dahei Mountain, Nanguan District, Yinma River Basin, and Songhua River Basin. In contrast, the regions with low habitat quality were predominantly found within construction land in municipal districts and counties, and the spatial differentiation of habitat quality gradually increased over time.

We normalized the four ecosystem services and added them using equal weights to calculate these ecosystem services' supply index. The mean values of the ecosystem services' supply index were 0.2306, 0.2385, and 0.2303 in 2000, 2010, and 2020, respectively. These values exhibited an upward trend from 2000 to 2010, followed by a subsequent decline in the subsequent decade. The geographical distribution of total ecosystem services in Changchun City exhibited a distinct pattern characterized by higher values in the southeastern areas and lower values in the northwestern areas (Figure 2e). The overall level was mostly low–medium. The high-value areas were mainly distributed in the forests in Jiutai, Erdao, Nanguan, and Shuangyang. The areas with a low value were mostly concentrated in water bodies and construction land. In the past 20 years, there has been a notable acceleration in the processes of urbanization and industrialization. The phenomenon of rapid urban development has given rise to a significant increase in construction land. This expansion has led to further encroachment into cultivated land and other ecological land, resulting in a large decrease in ecosystem services' supply.

### *3.2. Spatiotemporal Patterns of Ecosystem Services' Demand*

Rapid economic expansion is accompanied by a significant rise in the demand for ecosystem services. The land use intensity and average ecosystem service demand in Changchun in 2000, 2010, and 2020 were 298.94, 299.27, and 302.69 and 303.49, 304.62, and 308.02, respectively. As shown in Figure 3, we can see that the land use intensity, population, GDP, nighttime light brightness, and ecosystem services' demand in Changchun City increased throughout this period. Additionally, a spatial pattern emerged, with higher values in the southwestern areas and lower values in the northeastern areas of the city (Figure 3). The primary driver of land use change may be attributed to human activity. The land use changes between 2000 and 2020 encompassed significant alterations in several land types. Specifically, there was a substantial decline in the extent of cultivated land, accompanied by an expansion in both construction land and water bodies. Consequently, there was a rise in land use intensity, which serves as a clear manifestation of urban growth. The ecosystem services' demand and the four economic indicators all showed a high level in the municipal districts situated in the southwestern and built-up areas of counties, radiating from the center to the surrounding areas, and the value gradually decreased. Cultivated land constituted the predominant land type, extensively distributed across Changchun City, with a concentration in the central and northern areas. Cultivated land covered approximately 80% of the total area. These areas had a lower population and economy, leading to a lower demand for ecosystem services.




(**a**) (**b**) (**c**) (**d**) (**e**)

**Figure 3.** Spatiotemporal patterns of ecosystem services' demand in Changchun. (**a**) Land use intensity; (**b**) population; (**c**) GDP; (**d**) nighttime lighting intensity; and (**e**) ecosystem services' demand.

### *3.3. Analysis of Ecosystem Services' Supply and Demand Matching*

The average coordination index values for 2000, 2010, and 2020 in Changchun were 0.4601, 0.4554, and 0.4613, respectively (Figure 4). These values barely changed over time, and this indicates that there was a slightly uncoordinated relationship between the ecosystem services' supply and demand in Changchun. Using the natural breakpoint method, the degree of coordination was divided into five levels. From 2000 to 2020, the coordination index mainly exhibited a spatial distribution pattern characterized by high values in the southeast and low values in the northwest, while Yushu County, located in the northeast of Changchun, experienced a significant change. Most areas of Yushu had a basic coordination index in 2000; then, the index became classified under mid-misadjustment in 2010 and finally became mid-coordination in 2020. Highly coordinated regions were concentrated in the forest in the southeast of Changchun. Moderately coordinated areas were mainly composed of municipal districts, including Kuancheng, Luyuan, Chaoyang, Erdao, Shuangyang County, the southern part of Jiutai, and the built-up areas of other counties. The northern parts of Jiutai and Dehui mainly belonged to basic coordinated areas. Nong'an County was almost entirely located in mid-misadjusted areas and highly misadjusted areas.

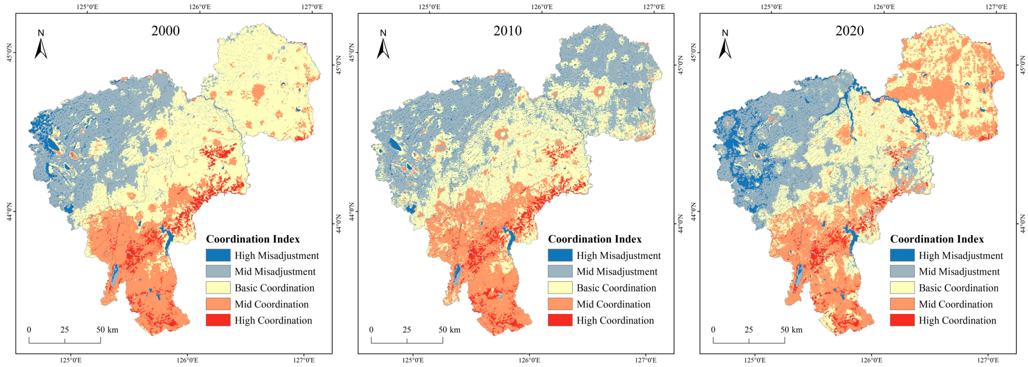



**Figure 4.** Coordination indexes of ecosystem services' supply and demand.

On account of the watershed data used in the water yield module, we analyzed the coordination between the ecosystem services' supply and demand at small watershed scales (Figure 5 and Table 3). The study area was divided into 80 small watersheds, most of which were at the level of basic coordination or above. In 2000, there was a total of 21 small watersheds with an imbalance between their ecosystem services' supply and demand, covering an area of 5442.01 km$^2$ and accounting for 26.4% of total area. The basic coordination type had the largest area of 6339.65 km$^2$, accounting for 30.76%. There were 18 small watersheds distributed in mid-coordination and 16 in high coordination. In 2010, the areas with misadjustment increased. The mid-misadjustment type had the largest area of 5597.62 km$^2$, accounting for 27.12%. The areas of basic coordination, mid-coordination, and high coordination were located in 20, 11, and 15 watersheds, respectively, covering an area of 3022.68 km$^2$, 4384.88 km$^2$, and 4885.88 km$^2$ and accounting for 14.66%, 21.27%, and 23.70% of the total area, respectively. In 2020, there were 29 watersheds distributed in mid-coordination. These had the largest area of 6389.90 km$^2$, accounting for 31.00% of the total area. The basic coordination types covered an area of 4620.99 km$^2$, and the proportion of other types accounted for less than 20% of the total area.

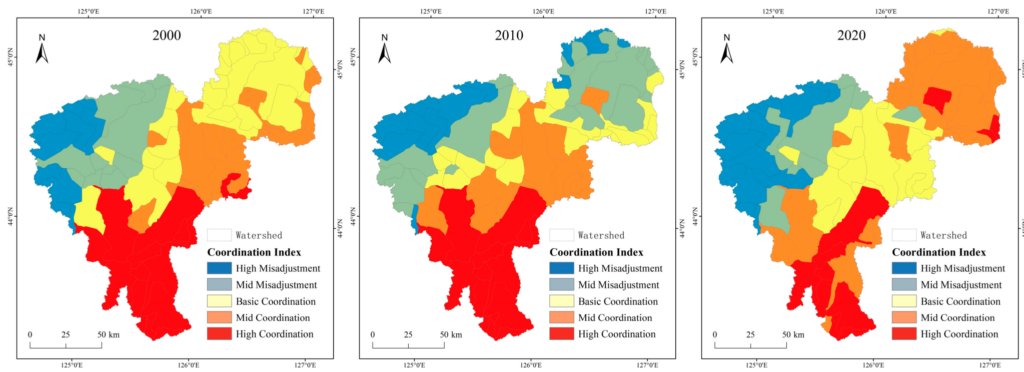



**Figure 5.** Coordination indexes of watersheds.

**Table 3.** Coordination indexes of watersheds.

| Coordination Index | 2000 | | | 2010 | | | 2020 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Quantity | Area ($km^2$) | Proportion (%) | Quantity | Area ($km^2$) | Proportion (%) | Quantity | Area ($km^2$) | Proportion (%) |
| High Misadjustment | 10 | 2200.84 | 10.68 | 14 | 2720.92 | 13.20 | 16 | 3782.40 | 18.35 |
| Mid-Misadjustment | 11 | 3241.17 | 15.72 | 20 | 5597.62 | 27.16 | 9 | 2721.60 | 13.20 |
| Basic Coordination | 25 | 6339.65 | 30.76 | 20 | 3022.68 | 14.66 | 14 | 4620.99 | 22.42 |
| Mid-Coordination | 18 | 3762.04 | 18.25 | 11 | 4384.88 | 21.27 | 29 | 6389.90 | 31.00 |
| High Coordination | 16 | 5068.25 | 24.59 | 15 | 4885.87 | 23.70 | 12 | 3097.07 | 15.03 |

Spatial differences in the matching of ecosystem services' supply and demand in Changchun from 2000 to 2020 could be obtained based on quadrant distribution. The results were categorized into four types: high supply–high demand (HH), high supply–low demand (HL), low supply–high demand (LH), and low supply–low demand (LL) (Figure 6). Overall, except for Yushu County, the spatial patterns of ecosystem services' supply and demand matching were relatively stable in Changchun City from 2000 to 2020. The areas of the HL matching type were primarily located in the east of Jiutai, the west of Nong'an, and the south of Shuangyang, composed of forest and grassland. Forests and grasslands can provide high ecosystem services, and humans rarely live there. The HH-type areas were concentrated in the south of the study area, including Shuangyang, the eastern part of Erdao, and the southern part of Jiutai. In 2010, its areas expanded and also covered Nanguan and Chaoyang. The largest LH-type areas were concentrated in the southwestern municipal districts, and the remaining areas were scattered in the built-up areas of various counties. These places were densely populated areas and had a high degree of economic development. This type of ecosystem services' supply and demand matching reflects the inherent conflict between ecosystem services' supply and human demand. The LL-type areas were predominantly located in the west and north of Changchun City. Cultivated land and water bodies were extensively distributed in these areas, and human activities were mainly focused on agricultural production. Consequently, there was a low supply of and a low demand for ecosystem services in these areas.

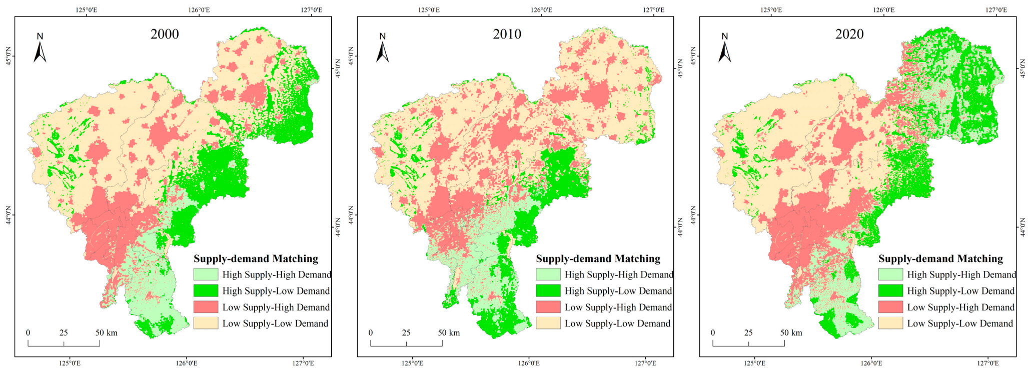



**Figure 6.** Matching between ecosystem services' supply and demand.

## 4. Discussion

### *4.1. Ecological Management Strategies for Different Areas*

Clearly, forests provided the highest ecosystem services compared to the other five land use types. The topographic elevation of a mountain plays a crucial role in determining its slope and aspect, constraining the potential for urban growth. Additionally, it occupies a prominent ecological niche in terms of water conservation and forest resources [38]. Therefore, the Dahei mountain range and surrounding areas located in the southeast of Changchun should be the primary ecological protection core area. In this area, we should pay attention to protecting ecosystem service functions, improving forest quality, and developing the under-forest economy and ecotourism appropriately, depending on the actual situation. Shuangyang District generally belongs to high supply–high demand areas and has a high coordination between the supply of and demand for ecosystem services. Comprehensive development of agriculture, towns, and ecology should be attended to in this region. Cultivated land exhibits a wide distribution in the center and north of Changchun City. Cultivated land has a production function, an ecological function, and a social function; among them, the production function is the main function of cultivated land. Although the ecosystem services offered by cultivated land are less than those of forests, the contribution of cultivated land to the whole of ecosystem services cannot be ignored due to its extensive coverage. Rapid urbanization has resulted in a significant decline in cultivated land, a decrease in ecosystem services' supply, and an increase in ecosystem services' demand in the north of Changchun. Most areas in the central and northern regions are in a state of basic coordination and misadjustment. Coordinating cultivated land protection and urban development should be a top priority in these areas. There are many lakes and grasslands in the west of Nong'an. Grassland ecosystems and water ecosystems are unstable compared to others. The ecosystem here is more fragile than that in other counties. Therefore, the western part of Nong'an, along with rivers and reservoirs in various regions, should also be considered as main areas for ecological protection.

The municipal districts, including Kuancheng, Chaoyang, Luyuan, Erdao, and Nanguan, serve as the economic and political centers of the whole city, which are key areas for ecological management. Despite the abundant human activities, large construction land area, and high land use intensity in these areas, there is still a large distribution of ecological land, which has made great contributions to ecological security. In terms of spatial patterns, most of the ecological land is distributed in the east, extending in a strip from the northeast to southwest, and forming an ecological barrier of central urban areas. The rest are scattered in the rivers, parks, and green spaces within the built-up areas (Figure 7). By accounting for the ecosystem services' supply of ecological land in the central urban area, we can see that the forest remains the most important source of ecosystem services' supply in ecological land types (Table 4). The water ecosystem also occupies a very important position in ecosystem services' supply, although it has the lowest supply compared to other ecological lands. In this area, the growth of construction land should be controlled by delineating urban development boundaries. It is important to protect urban parks and green spaces, as well as forests and reservoirs, to enhance the value of ecosystem services.

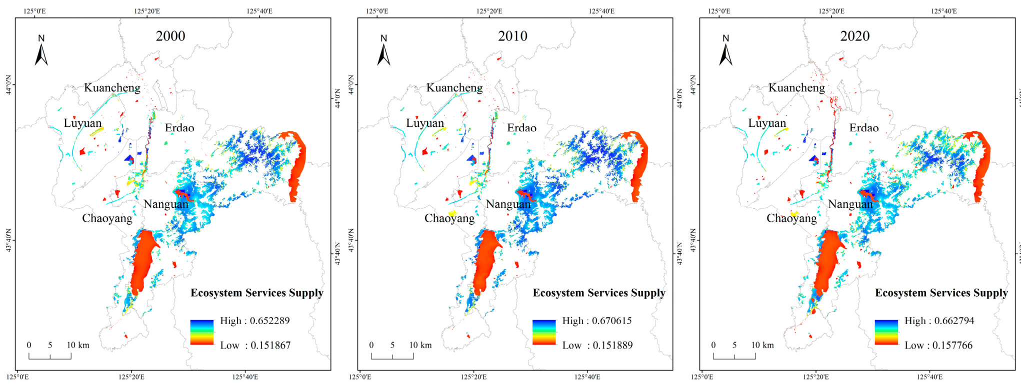



**Figure 7.** Ecosystem services' supply of ecological land in central urban areas.

**Table 4.** Evaluation of ecosystem services of ecological land in central urban areas.

| Ecosystem Services' Supply | 2000 | | | 2010 | | | 2020 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Forest | Grassland | Water Body | Forest | Grassland | Water Body | Forest | Grassland | Water Body |
| Water yield ($\times 10^7$ m$^3$) | 2.65 | 1.40 | 0.00 | 6.92 | 2.82 | 0.00 | 3.16 | 1.50 | 0.00 |
| Carbon storage ($\times 10^5$ t) | 44.50 | 4.88 | 6.55 | 44.81 | 5.23 | 6.51 | 43.16 | 4.56 | 7.28 |
| Soil conservation ($\times 10^5$ t) | 19.68 | 3.24 | 1.18 | 41.12 | 7.01 | 1.66 | 19.51 | 3.46 | 1.59 |
| Habitat quality | 0.71 | 0.58 | 0.65 | 0.71 | 0.58 | 0.65 | 0.65 | 0.53 | 0.64 |

### *4.2. Factors Affecting Ecosystem Services' Supply*

Land use change is the primary influencing factor on the change in ecosystem services' supply and demand. The InVEST model focuses on the correlation between land use and ecosystem services. Carbon storage and habitat quality require land use data and various parameters to run the modules. The parameters remain unchanged during this process, so variations in carbon storage and habitat quality are only attributed to land use changes in a period of time. Except for land use, annual water yield is affected by other factors, including annual precipitation, annual evaporation, available plant water capacity, and root depth. The last two parameters were extracted from the soil data, but data on water bodies were missing in the HWSD, so we set them to 0. This would explain why water bodies had the lowest water yield. An artificial surface has less vegetation and less evapotranspiration. The growth of urban development has led to an increase in impermeable surface area, which stops surface water infiltration and changes the water balance [41]. A forest has strong evapotranspiration and infiltration of surface runoff. Therefore, water yield was high for construction land and low for forest land. There was a significant difference in the value and distribution of precipitation in 2010 compared to those in 2000 and 2020, resulting in a high water yield in Changchun in 2010. Precipitation also affects soil conservation. There exists a positive correlation between precipitation and the rainfall erosion factor, leading to an increase in soil conservation. Consequently, in the past two decades, carbon storage and habitat quality declined, and the maximum values of water yield and soil conservation appeared in 2010. The ecosystem services' supply increased first and then decreased from 2000 to 2020.

### *4.3. Limitations and Improvement*

Ecosystem services come from the logistics, energy flow, and information flow of ecosystems. To assess the value of ecosystem services, it is necessary to decompose complex systems (structures and processes) into several service functions first. And the functions should be able to generate benefits that represent human gains from the ecosystem directly or indirectly, including its resource supply, environmental regulation, cultural entertainment, and production support. In the Millennium Ecosystem Assessment (MA) of the United Nations, ecosystem services are classified into four types: providing, regulating, supporting, and cultural. Costanza et al. [2] subdivided ecosystem services into 17 types. Xie et al. [29] further divided ecosystem services into 11 types based on the understanding of Chinese people and decision makers on ecological services. Based on the actual situation and data accessibility in Changchun City, in this study, we chose the four services, water yield, carbon storage, soil conservation, and habitat quality, to calculate the ecosystem services' supply. These services covered the providing, regulating, and supporting services of the ecosystem. It was difficult to obtain spatial data for cultural services. This should be improved upon in future research. Regarding ecosystem services' demand, we used land use intensity, population, GDP, and nighttime lighting to represent demand, without quantifying the demand for each ecosystem service. In future research, we will integrate more types of ecosystem services into the estimation of the supply and calculate the corresponding demand for various ecosystem services using real consumption data.

## 5. Conclusions

In this study, by selecting a key industrial base in the northeast of China, Changchun, as the research area, we preprocessed multisource data, including land use, DEM, precipitation, evapotranspiration, soil, population, GDP, and nighttime lighting, based on ArcGIS 10.8. We selected the water yield, carbon storage, soil conservation, and habitat quality to quantitatively assess ecosystem services' supply in 2000, 2010, and 2020 using the InVEST model. Simultaneously, the land use intensity, population, GDP, and nighttime lighting data were used to estimate the ecosystem services' demand. Then, we introduced the coordination index and spatial matching types to analyze the correlation between the ecosystem services' supply and demand. This study analyzed the spatiotemporal change in the supply and demand of ecosystem services, along with their relationship, in Changchun City from 2000 to 2020, which could offer a scientific foundation for ecological management. The conclusions are the following:

(1) Variations in different types of ecosystem services' supply showed significant differences in both the temporal and spatial dimensions. From 2000 to 2020, carbon storage and habitat quality declined, while water yield, soil conservation, and the total ecosystem services' supply increased first and then decreased. Except for the water yield, other ecosystem services and the total supply exhibited a distribution with higher values in the southeast and lower values in the northwest. From 2000 to 2020, land use intensity, population, GDP, nighttime light brightness, and ecosystem services' demand in Changchun City increased. These indicators exhibited higher values in the southwest region, while comparatively lower values were seen in the northeast region.

(2) The relationship between ecosystem services' supply and demand in Changchun was slightly uncoordinated. The regions characterized by a low supply of and high demand for ecosystem services mostly encompassed central urban regions that exhibited a high degree of socioeconomic development. Conversely, the regions characterized by a high supply and low demand were mostly hilly areas with a sparse population that were situated at higher altitudes.

(3) Land use change was the primary influencing factor on change in the ecosystem services' supply and demand in Changchun. In the future, it is imperative for sustainable urban development strategies to protect cultivated and ecological lands. Concurrently, there is a need to extensively enhance the economic, social, and ecological benefits associated with land. This approach will facilitate the coordinated development of cities, agriculture, and ecology.

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