

Article

Analysis of Spatio-Temporal Relationship Between Ecosystem Services and Human Footprints Under Different Human Activity Gradients: A Case Study of Xiangjiang River Basin

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Abstract: Clarifying the relationship between human activities and the provision of ecosystem services has received significant interest in recent years because of a growing need for sustainable socio-ecological system development. Using multi-source remote sensing data, we assessed the spatial and temporal distribution of the human footprint index and five ecosystem services under four human activity gradients from 2010 to 2020 in the Xiangjiang River Basin. The five ecosystem services include water supply, soil conservation, food production, habitat quality, and carbon sequestration. The relationship between human footprint and ecosystem services was analyzed from quantitative and spatial perspectives. The results showed that over the past 10 years, water supply and habitat quality decreased by 4.59% and 16.49%, respectively. The other three services increased, and the upstream area of the basin had a higher level of ecosystem services provision. The human footprint index increased by 28.83% over the 10 years and was characterized by point and patchy clustering in the middle and lower reaches. In terms of quantitative characteristics, the relationship between human footprint and ecosystem services was primarily negative. The ecosystem services were sensitive to the human footprint index within the 0–0.4 range. In terms of spatial characteristics, the relationship was dominated by trade-offs. The risky “high–low” trade-offs were mainly distributed in the middle and lower reaches. As the gradients of human activity increased, the maximum fluctuation in ESs was 43%, and the maximum fluctuation in human footprint was 28%, making their relationship more complex. Our results identified response thresholds of ecosystem services to human activities, providing a guide for ecological management and sustainable development of basins.

Keywords: ecosystem services; human activity gradient; land use; socio-ecological balance; basin management

1. Introduction

Ecosystem services (ESs) are the sum of the goods and benefits that humans obtain from natural ecosystems [1]. Serving as a bridge between human society and natural ecosystems, ESs are a crucial foundation for human well-being [2]. Since the Industrial Revolution, human demand for ESs has increased dramatically with rapid economic and population growth. Increased human activities have resulted in ecological degradation [3], loss of

biodiversity [4], and other issues, which have consequently reduced the supply capacity of ESs [5]. Therefore, understanding the relationship between human activities and the supply of ESs is critical to socio-ecological system stability. ESs were generated by natural ecosystems and used in human societies. In recent years, studies of the supply–demand balance of ESs have been used to characterize human impacts on ESs [6]. These studies have typically used per capita consumption for specific services combined with population data to estimate the total human demand for ESs within a region [7]. Subsequently, studies usually calculated indicators such as ESs supply–demand ratio index [8], coupling coordination degree [9], etc. to reflect the potential impacts of human activities on ESs. Therefore, scholars have often measured indicators such as per capita consumption in terms of administrative units, the scale of these studies focused more on national, provincial, and city scale regions. Spatial mismatches were also found in these studies [10]. However, these studies were more from the perspective of human needs and have lacked in-depth exploration of the mechanisms by which the type and intensity of human activities affect ESs.

In addition, some studies have focused on specific anthropogenic events and analyzed the impacts of different types of human activities on ESs [11]. The three main types of these anthropogenic events include urbanization [12], land use change [13], and landscape fragmentation [14]. In these studies, scholars have visualized anthropogenic events by quantifying different indicators. For example, population density data, gross regional product data, and the proportion of built-up land were used to quantify the demographic, economic, and urbanization impacts of urbanization [15]. Land use transfer matrices were used to quantify the dynamics of human activities in land management [16]. Landscape pattern indices were used to quantify the modification of surface patterns by human activities [17]. Combined with multi-source remote sensing data, such as nighttime lighting and land use, the human footprint index (HFP) integrates economic, demographic, and transportation environmental pressures [18], and has been widely used to assess the intensity of human activities in recent years [19–21]. In quantifying ESs, market valuation [22] and modeling approaches [23] have been the dominant methods in current research. These studies have typically used statistical analysis [24], linear regression [25], random forest regression [26], and scenario modeling [27] to analyze the impacts of different human activity types on ESs. In recent years, a growing number of studies have found that the direct or indirect impacts of human activities on ESs result in a complex relationship between the two [28,29]. Consequently, traditional linear fitting and statistical analyses were limited in their ability to resolve complex influence mechanisms. In addition, spatial heterogeneity and dependence [30], non-stationary response [31], spillover effects [32] have been found in these case studies. These findings illustrated that scale effects are key to resolving the mechanisms of human activity impacts on ecosystem services.

The Xiangjiang River Basin is an essential part of the Yangtze River Basin and the Nanling ecological barrier [33]. It also hosts the Xiangjiang River Economic Belt [34] and is one of the most important rice-growing areas in China [35]. With population growth and economic development, achieving a balance in the socio-ecological system has become a significant issue in this region. It is an ideal area for studying sustainable development in the relationship between humans and the environment, as it is a region intertwined with human activities and natural ecology. Recently, researchers focused on urbanization [36], land use change [37], and ESs supply–demand balance [38] in the basin. However, these studies do not consider the differences between the upstream and downstream of the basin. This leads to large differences in the upstream and downstream manifestations of spatial heterogeneity in the relationship between human activities and ESs [36].

In previous studies, some scholars have used human activity gradients to measure different levels of human activity [39], which is suitable for studying differences in human activities upstream and downstream of a basin. In this study, we used nighttime lighting data, protected area boundaries, and land use data to delineate human activity gradients in the Xiangjiang River Basin. We analyzed the relationship between the HFP and ESs under four human activity gradients. The objectives of this study were as follows: (1) to

characterize the spatial and temporal variations of five ESs (water supply, soil conservation, food production, habitat quality, and carbon sequestration) and the HFP in the Xiangjiang River Basin; (2) to analyze the relationship between the HFP and ESs in the Xiangjiang River Basin from the perspective of quantitative and spatial characteristics. This study provides a reference for sustainable basin management, which aims at the coordinated development of socioeconomic and ecological protection.

2. Materials and Methods

2.1. Study Area

The Xiangjiang River Basin is part of the Dongting Lake system of the Yangtze River Basin, covering a total area of 92,100 km². The Xiangjiang River Basin is dominated by a subtropical monsoon climate, with an average annual temperature between 16 °C and 18 °C and an average annual precipitation between 1200 and 1700 mm. The topography of the basin is dominated by mountains and hills, characterized by a high distribution in the south and a low distribution in the north. The average elevation is 326 m. The Xiangjiang River Basin is not only the most urbanized and populated area in Hunan Province but is also a significant area for agricultural production. In 2010, the permanent population of the nine cities within the basin reached 46.87 million. By 2020, the population of the nine cities reached 48.74 million, which accounted for 73.35% of the total population of Hunan province (<https://tjj.hunan.gov.cn/tjfx/hntjnj/index.html>, accessed on 5 June 2023). Most of this population is concentrated in the urban agglomeration downstream. In 2010, the total cropland area in the basin was 2.56 million ha. By 2020, the total cropland area decreased by 3000ha, which still accounted for 70.44% of the total cropland in Hunan Province (<https://tjj.hunan.gov.cn/tjfx/hntjnj/index.html>, accessed on 5 June 2023). Most of this cropland is located in the middle reaches of the basin. Rice cultivation is the mainstay, with the province's output reaching 26.4 billion kg, ranking second in China. In 2010, the total forest land area in the basin was 5.47 million ha. By 2020, the total forest land area in the basin was 5.31 million ha, which accounted for 57.7% of the total basin (Figure 1). The main stem of the Xiang River originates in the southwestern mountains and is supplemented by tributaries originating in the southeastern mountains. It then flows in a northeasterly direction through the cultivated plains in the central part of the basin. Eventually, it passes through the downstream Changsha–Zhuzhou–Xiangtan urban agglomeration and is injected into the Dongting Lake in the north. In summary, the Xiangjiang River Basin is affected by various human activities at different intensities throughout its upper (above Yongzhou), middle (Yongzhou–Hengyang), and lower reaches (below Hengyang) [40]. This makes it a perfect area to examine the intricate relationship between humans and land.

2.2. Data Collection and Preprocessing Processes

(1) Land use data

The land use data came from the Globeland30 dataset, with a spatial resolution of 30 m. It included seven classes: cropland, forest land, grassland, wetland, water area, built-up land, and unused land.

(2) Soil data

Soil data includes information on soil maximum root depth data, soil available water data, and soil particle size data. The data on soil root depth comes from the soil type data of the Resource and Environment Data Center of the Chinese Academy of Sciences, with a spatial resolution of 1 km. Soil available water data came from the World Soil Information Data Platform, with a resolution of 250 m. This data comprised raster data on soil available water at seven depths from 0 to 200 cm below the ground surface. The soil particle size data came from the Harmonized World Soil Database (HWSD), published by the United Nations Food and Agriculture Organization (FAO), and had a resolution of 1 km. The data contained 12 attribute features, including soil particle size.

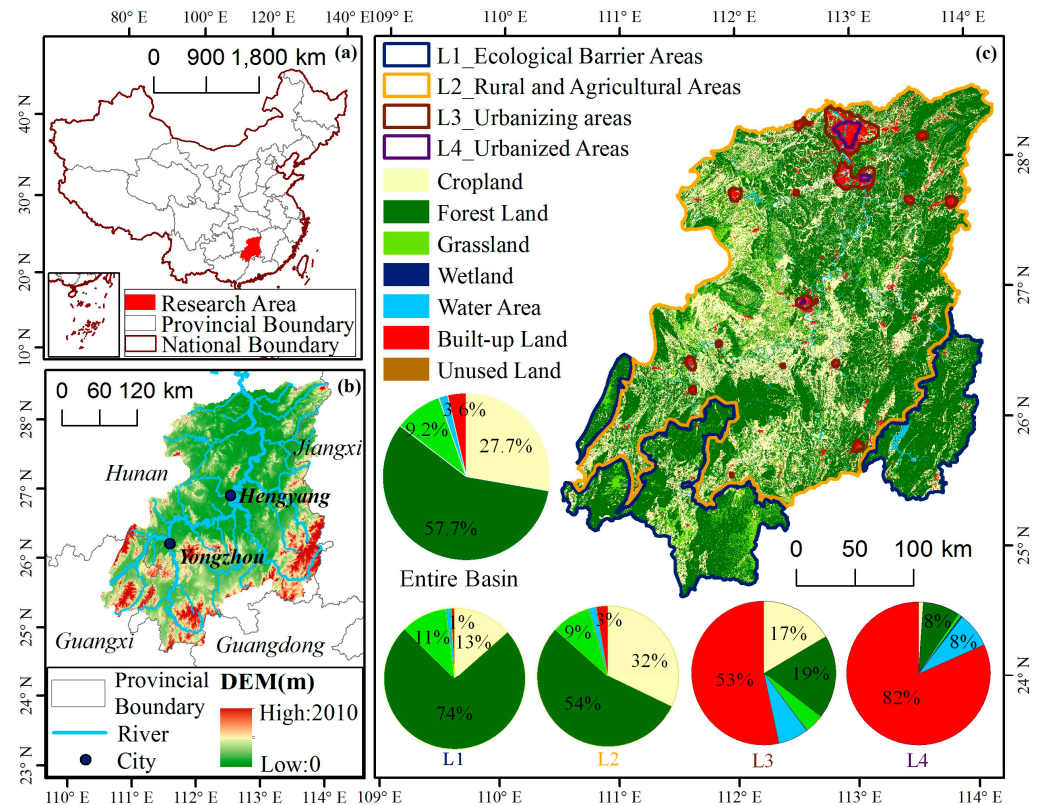


Figure 1. Basic information of the study area. (a) Location of Xiangjiang River Basin; (b) elevation and water distribution of Xiangjiang River Basin; (c) land use and land cover of the Xiangjiang River Basin. The pie chart in Figure 1c on the left side of the graph shows the percentage of land use area in the entire basin. L1–L4 in Figure 1c represents four different human activity gradient areas (ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas). The pie charts below show the percentage of land use area in the four areas.

(3) Potential evapotranspiration data

Potential evapotranspiration data came from the NASA MOD16A2GF dataset, with a resolution of 500 m, comprising five data layers, including total potential evapotranspiration.

(4) Normalized difference vegetation index data

Normalized difference vegetation index data came from the NASA MOD13Q1 dataset at a resolution of 250 m, with a 16-day collection period for data transit.

(5) Topographic data

The digital elevation data came from the ASTERGDEM dataset with a resolution of 30 m.

(6) Meteorological data

Meteorological data came from near-surface meteorological observations at 162 national meteorological stations in six provinces in South China. Three indicators, including precipitation, average temperature, and solar radiation, were selected in this study.

(7) Traffic network data

The traffic network data came from vector data from the OpenStreetMap platform, which contains 27 roads of different classes and categories.

(8) Population density data

Population density data came from the China Population Spatial Distribution Kilometer Grid dataset of the Resources and Environment Data Center of the Chinese Academy of Sciences, with a resolution of 1 km. This dataset was made by considering land use types, nighttime light brightness, settlement density, and other population distribution influences.

(9) Nighttime light data

The nighttime lighting index data came from the data product released by the research team of Zuoqi Chen at Fuzhou University, with a resolution of 500 m. This data product was based on DMSP-OLS and NPP-WIIRS nighttime lighting data corrections.

(10) Statistical data

The statistical data came from the statistical yearbook issued by the Hunan Provincial Bureau of Statistics. This study mainly referred to data on population, socio-economics, and agricultural production.

We aggregated all the spatial data to 250 m through simple averaging to match the spatial resolution of soil and NDVI. For more information on data sources, refer to Table A1.

2.3. Classification of the Gradient of Human Activity

To clarify the complex human–land relationship within the Xiangjiang River Basin, four human activity gradient areas were delineated. We used the land use and land cover, nighttime light index, urbanization processes, and ecological environment to class the four human activity gradients (Figure 1c).

$$\left\{ \begin{array}{ll} NTL_{2010} > 50, NTL_{2020} > 50, & L4 \\ NTL_{2010} < 50, NTL_{2020} > 50, & L3 \\ Biodiversity Conservation, & L1 \\ Others, & L2 \end{array} \right. \quad (1)$$

In Equation (1), NTL_{2010} and NTL_{2020} are the nighttime light data (NTL) from 2010 to 2020. *Biodiversity Conservation* represents China's biodiversity conservation priority areas designated by the Ministry of Ecology and Environment in 2015 (https://www.mee.gov.cn/gkml/hbb/bgg/201601/t20160105_321061.htm, accessed on 10 July 2023).

The L4 gradient areas are the urbanized areas, which are mainly in the urban agglomeration area in the lower part of the basin (Figure 1c). Areas with a nighttime light index greater than 50 in each of the 10 years are classified within this gradient [15]. These areas are dominated by built-up land, which accounts for 82% of the area (Table A2).

The L3 gradient areas are urbanizing areas, which are distributed in a ring shape downstream, and in a scattered pattern in the middle reaches of the basin (Figure 1c). Areas where the nighttime light index surpassed 20 in 2020, but were below 20 in 2010, are classified within this gradient. Built-up land makes up 53% of these areas, followed by forest land with 19%, and cropland with 17% (Table A2).

The L1 gradient areas are ecological barrier areas, which are mainly in the mountainous and hilly regions downstream (Figure 1c). Priority biodiversity conservation areas within the basin are classified within this gradient. These areas are dominated by forest land with 74% of the area, along with 13% of the cropland and 11% of the grassland (Table A2).

The L2 gradient areas are rural and agricultural areas, which are mainly in the middle reaches of the basin and cover the largest area (Figure 1c). Excluding the L4, L3, and L1 gradient areas, the remaining areas are classified within this gradient. Forest land and cropland are the main land use in these regions, accounting for 54% and 32%, respectively (Table A2).

2.4. Methods

2.4.1. Ecosystem Services Assessment

Ecosystem services were selected in this study based on the ecological conditions and economic development characteristics of the basin. We selected five services: water supply (WS), habitat quality (HQ), carbon sequestration (CS), food production (FP), and soil conservation (SC). These were characterized by surface water yield, soil conservation, food yield, habitat quality index, and net primary productivity, respectively.

(1) Water supply service

We evaluated WS by surface water yield [41]. We calculated surface water yield by the annual water yield module of the InVEST model. In the InVEST model, the land use, soil properties, surface runoff, evapotranspiration, rainfall, and topography data were used. To assess the contribution of water yield in a primary basin, watershed delineation was required. The DEM elevation data was used to tune threshold gradient parameters in the SWAT hydrologic model. According to the water balance equation, the water yielded in each grid cell is the precipitation minus the evapotranspiration.

$$WS(x) = (1 - \frac{AET(x)}{P(x)}) \cdot P(x), \quad (2)$$

In Equation (2), $WS(x)$ is the annual water yield, $AET(x)$ is the annual evapotranspiration, $P(x)$ is the annual precipitation, and the raster value of the output data is in mm.

(2) Habitat quality service

We evaluated HQ by the habitat quality index [42]. In the InVEST model, the habitat quality index was calculated through four factors: the impact of the threat factor on each land use type, the maximum distance of impact of the threat factor, the sensitivity of the habitat to the threat factor, and the establishment of protected areas.

$$HQ_{xy} = H_j [1 - (\frac{D_{xy}^2}{D_{xy}^2 + k^2})], \quad (3)$$

In Equation (3), HQ_{xy} is the habitat quality index of the grid cell (x, y) , H_j is the habitat suitability parameter of the land use and land cover (LULC) type j , D_{xy} is the stress index of the grid cell x of the LULC type j , and k is the half-saturation constant. In this study, cropland, water areas, built-up land, unused land, and roads were selected as threat factors. The factor parameters were referred to the related study by Schleupner and Schneider in 2013 [43]. The habitat quality index ranges from 0 to 1.

(3) Carbon sequestration service

We evaluated CS by net primary productivity (NPP). NPP directly reflects the production capacity and carbon dioxide fixation ability of vegetation under natural conditions. It also indirectly reflects the impact of climate change and human activities on surface vegetation [44]. We calculated NPP by the CASA model through two factors: photosynthetically active radiation absorbed by plants (APAR) and actual light energy utilization (ϵ).

$$CS(x, t) = APAR(x, t) \times \epsilon(x, t), \quad (4)$$

In Equation (4), x represents the grid cell; t represents the time, $CS(x, t)$ is the net primary productivity ($t \cdot ha^{-1} \cdot a^{-1}$) of the vegetation on grid cell x in month t , $APAR(x, t)$ is the photosynthetically active radiation ($gC \cdot m^{-2} \cdot month^{-1}$) absorbed by the vegetation on grid cell x in month t , and $\epsilon_{(x,t)}$ is the actual light energy utilization ($gC \cdot MJ^{-1}$) of the vegetation on grid cell x in month t .

(4) Food production service

We evaluated FP by food yield [15]. A significant positive correlation was found between the NDVI and food yield [45]. Therefore, we calculated food yield by the MODIS NDVI and statistical yearbook data. NDVI data was used to rasterize crop yield data from statistical yearbooks.

$$FP_i = \frac{FP_{sum}}{NDVI_{sum}} \times NDVI_i, \quad (5)$$

In Equation (5), FP_i represents the food yield (t) corresponding to the cropland grid cell i , FP_{sum} represents the total food yield (t) in the statistical yearbook, $NDVI_{sum}$ represents the sum of the NDVI of the cropland grid cell, and $NDVI_i$ represents the value of the NDVI corresponding to the cropland grid cell i .

(5) Soil conservation service

We evaluated SC by soil conservation. We calculated soil conservation by the difference between potential soil erosion and actual soil erosion using the RUSLE equation [46]. The potential soil erosion is the amount of soil erosion under conditions with no soil conservation measures and vegetation cover.

$$A_p = R \times K \times LS, \quad (6a)$$

$$A_r = R \times K \times LS \times C \times P, \quad (6b)$$

$$SC = A_p - A_r, \quad (6c)$$

In Equation (6c), SC denotes the soil conservation in the basin ($t \cdot hm^{-2} \cdot a^{-1}$), A_p denotes the potential soil erosion ($t \cdot hm^{-2} \cdot a^{-1}$), and A_r denotes the actual soil erosion ($t \cdot hm^{-2} \cdot a^{-1}$). In Equations (6a) and (6b), R denotes the precipitation erosion factor; K denotes the soil erodibility factor; L and S denote the slope factor and slope length factor, respectively; C is the vegetation cover factor; P is the soil and water conservation factor.

2.4.2. Human Footprint Index Assessment

We used the HFP to assess the impact of human activities on biodiversity and habitat quality [47,48]. Referring to the framework of Venter et al. [19]. and Shen et al. [49], the HFP was calculated using seven environmental pressures: degree of urbanization, cropland, grassland, population density, nighttime lighting index, railway, and roads.

$$HFP = P_{BUL} + P_{CL} + P_{GL} + P_{POP} + P_{NTL} + P_{Rail} + P_{Road}, \quad (7)$$

In Equation (7), HFP is the human footprint index, quantified by the sum of environmental pressures from different human activities.

P_{BUL} is the pressure from the degree of urbanization. We used the NTL data to calculate P_{BUL} . NTL values greater than 20 were defined as built-up areas and assigned a pressure value of 10. NTL values less than 20 were defined as non-built-up areas and assigned a pressure value of 0 [49].

P_{CL} and P_{GL} are the pressure from cropland and grassland, respectively. We calculated P_{CL} and P_{GL} by the land use data. Cropland was assigned a pressure value of 7 and grassland was assigned a pressure value of 4 [49].

P_{POP} is the pressure from population density. Referring to Venter et al. [19], a population density greater than 1000/km² was assigned a pressure value of 10. We calculated the population density of less than 1000/km² as follows:

$$P_{POP} = 3.333 \times \log(POP_{dens} + 1) \quad (8)$$

In Equation (8), P_{POP} represents the population density pressure value, POP_{dens} represents the population density of 1000/km².

P_{NTL} is the pressure from NTL. NTL values less than 6 were assigned a pressure value of 0. NTL values greater than 6 were normalized to the maximum and minimum raster values of the 2010 and 2020 data, then re-assigned a pressure value of 0–10 using the equidistant breakpoint method.

P_{Rail} and P_{Road} is the pressure from railways and roads. The traffic network data was used to calculate P_{Rail} and P_{Road} . A pressure value of 8 was assigned within the 1 km buffer zone of the railway. A pressure value of 0–8 was assigned within the 0–15 km buffer zone of the roads.

2.4.3. Relationship Analysis Between Ecosystem Services and Human Footprint

To reflect the correlation between ESs and the HFP in terms of quantitative characteristics and spatial distribution characteristics, Pearson's correlation coefficient, nonlinear curve fitting, and Moran's I index were calculated. The nonlinear curve fitting, including polynomial, exponential, logarithmic, and power-law functions, was tested. The adjusted R^2 was used to determine the final fit function.

The spatial correlation between ESs and HFP was calculated by the bivariate global Moran's I index. The similarity and heterogeneity of the spatial distribution of ESs and HFP were calculated by the bivariate local Moran's I index and the LISA map.

Where the bivariate global Moran's I index is greater than 0 means that changes in ESs and the HFP over 10 years are spatially positively correlated, and vice versa is a negative correlation. An index closer to 1 represents a more significant synergy between ESs and HFP, and an index closer to -1 represents a more significant trade-off between ESs and HFP. In addition, five types of spatial relationships between ESs and the HFP were presented in the LISA plot: insignificant, "high-high" clustering, "low-low" clustering, "high-low" clustering, and "low-high" clustering. In this study, the statistical significance of the bivariate Moran's I index was analyzed by Monte Carlo simulation test with $p < 0.1$, showing that the spatial correlation between ESs and HFP was statistically significant and credible.

3. Results

3.1. Spatial and Temporal Changes in Ecosystem Services

In terms of spatial distribution, high HQ, CS, and SC value areas were mainly found upstream, high FP value areas were mainly found midstream, and high WS value areas were mainly found downstream (Figure 2). The high-value areas of HQ ($HQ > 0.99$) were primarily situated in mountainous and hilly regions of the southwest and southeast upstream. The low-value areas of HQ ($HQ < 0.36$) mainly lay in the river valleys of the middle and lower reaches of the basin. HQ showed a slight increase in most areas over the 10-year period. The high-value areas of CS ($CS > 1124.79 \text{ gC} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$) were extensively distributed on the eastern side of the basin. The low-value areas of CS ($CS < 617.84 \text{ gC} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$) were primarily distributed in the middle and lower reaches of river valley areas of the basin and the plain areas in the northwestern part of the lower reaches. CS showed a slight increase in the eastern and southern areas over the 10-year period. The high-value areas of FP ($FP > 18.36 \text{ t}$) were mainly in the plains west of the middle and lower reaches of the basin. The low-value areas of FP ($FP < 15.43 \text{ t}$) primarily surrounded the urban agglomeration downstream. FP increased in the central areas over the 10-year period. The high-value areas of SC ($SC > 606.88 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) were predominantly in the upper part of the basin. The low-value areas of SC ($SC < 557.67 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) were widely distributed across the plains in the middle and lower valley plains. SC increased significantly in the southern areas during the 10-year period. The high-value areas of WS ($WS > 1255.63 \text{ mm}$) were mainly found in the southern and southwestern upstream river valleys, downstream plains, and built-up areas. The low-value areas of WS ($WS < 1022.79 \text{ mm}$) were primarily in the eastern part of upstream, the middle basin, and the western regions of downstream. WS showed an increase in the south and a decrease in the north over the 10-year period.

In terms of quantitative characteristics, except for HQ and WS, the other three ESs increased during the 10 years. The five types of ESs showed an initial increase followed by a decrease in the intensification of human activities (Table 1, Figure 3). In the whole basin, the average supply levels of HQ in 2010 and 2020 were 0.71 and 0.68, respectively. The overall level of HQ declined by 4.59% over the 10 years, with a significant decline in the areas surrounding downstream urban agglomerations. The average supply levels of CS in 2010 and 2020 were $638.55 \text{ gC} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ and $1102.44 \text{ gC} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$, respectively. The overall level of CS increased by 72.65%, with the most pronounced increase in the upper hilly terrain. The average supply levels of FP in 2010 and 2020 were 5.22 t and 5.47 t, respectively. The overall FP level increased by 4.69%, with a significant increase

in the midstream central region. The average supply levels of SC in 2010 and 2020 were $275.01 \text{ t} \cdot \text{h} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ and $377.8 \text{ t} \cdot \text{h} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$, respectively. The overall level of SC increased by 37.38%, with a significant increase in the upper hilly terrain. The average supply levels of WS in 2010 and 2020 were 1278.79 mm and 1067.89 mm, respectively. The overall level of WS decreased by 16.49%, with a slight decrease in most downstream areas.

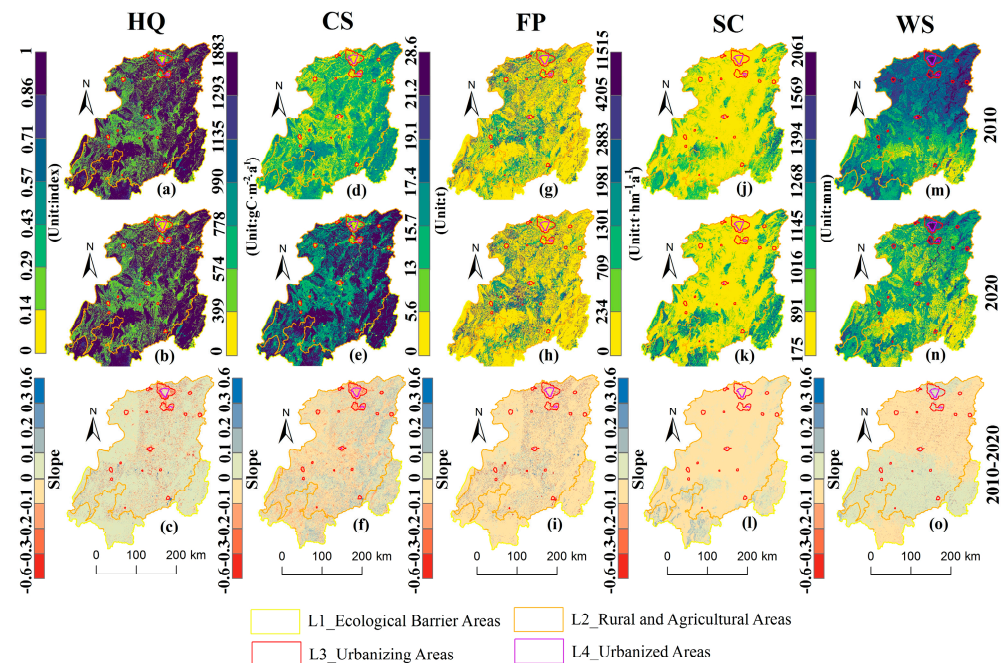


Figure 2. Spatial and temporal changes in ecosystem services in Xiangjiang River Basin. (a–c), (d–f), (g–i), (j–l), and (m–o) represent the spatial distribution of habitat quality service, carbon sequestration service, food production service, soil conservation service, and water supply service in the whole basin in 2010, 2020, and 2010–2020 slope, respectively. L1–L4 in the figure represents four different human activity gradient areas (ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas).

Table 1. The average level of ecosystem services provisioning in the basin and within each human activities gradient region in 2020. L1–L4 in the table represents ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas, respectively. HQ, CS, FP, SC, and WS represent habitat quality, carbon sequestration, food production, soil conservation, and water supply ecosystem service, respectively.

Human Activity Gradients	HQ Index		CS $\text{gC} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$		FP t		SC $\text{t} \cdot \text{h} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$		WS mm	
	2010	2020	2010	2020	2010	2020	2010	2020	2010	2020
L1	0.90	0.90	846.71	1356.57	2.13	2.08	1121.32	1302.45	1114.96	959.66
L2	0.70	0.68	634.91	1105.26	5.49	5.82	224.42	324.97	1282.06	1063.46
L3	0.40	0.18	360.56	556.78	4.46	2.56	38.78	51.49	1483.41	1371.58
L4	0.17	0.05	227.38	448.98	0.95	0.21	47.18	70.69	1608.58	1529.18
Entire Basin	0.71	0.68	638.55	1102.44	5.22	5.47	275.01	377.8	1278.79	1067.89

From the perspective of gradient changes in human activity, areas with high levels of human activity exhibit lower levels of HQ, CS, and SC (Table 1, Figure 3). By contrast, areas with high levels of human activity exhibit higher levels of WS. The level of FP showed an increase–decrease trend as the gradient of human activity increased. Over the decade, HQ showed the most significant decrease in the L4 gradient areas, dropping by 68.48% compared to 2010. CS showed the most notable increase within the L4 gradient areas, rising

by 97.45% from 2010 to 2020. The FP decreased slightly in the L1 gradient area and showed a significant drop in the L3 and L4 gradient. However, the L2 gradient areas saw a slight increase of 6.16% compared to 2010. SC showed the most significant increase in L4 gradient areas, increasing by 49.81% from 2010 to 2020. Conversely, WS showed the most significant decrease in L2 gradient areas, decreasing by 17.05% from 2010 to 2020.

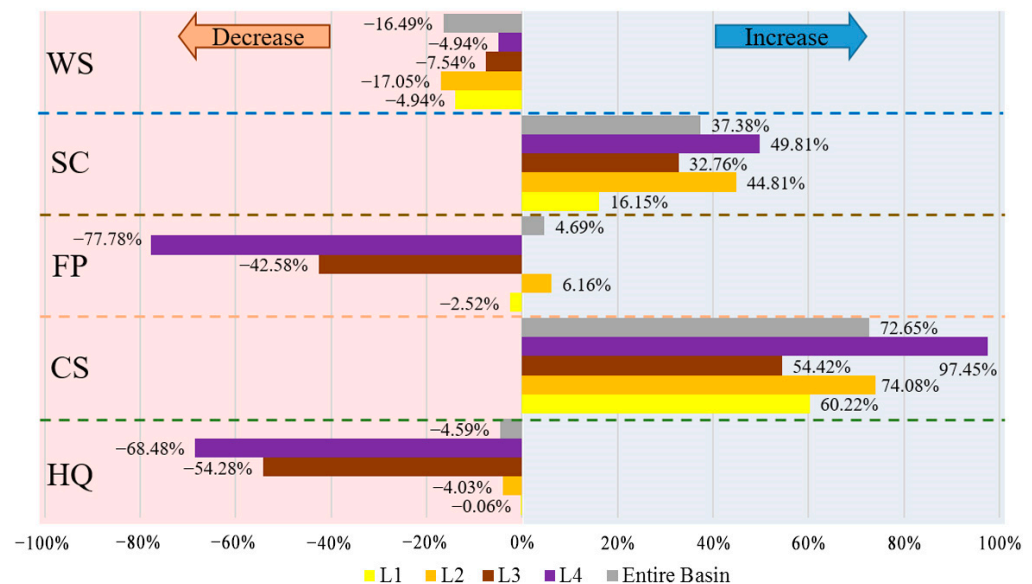


Figure 3. Rate of change in the average level of provisioning of ecosystem services in the basin and across the human activity gradients over 10 years. L1–L4 represents ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas, respectively. HQ, CS, FP, SC, and WS represent habitat quality, carbon sequestration, food production, soil conservation, and water supply ecosystem service, respectively.

3.2. Spatial and Temporal Changes in Human Footprint

The HFP in the basin showed a 28.83% increase (Table 2) over 10 years, which included a notable agglomeration effect in the urban and town areas (Figure 4). The high-value areas of HFP ($HFP > 0.29$) were mainly in the lower valley plain areas in the northern part of the basin. The low-value areas of HFP ($HFP < 0.14$) were mainly in upstream mountainous areas in the southwest and southeast of the basin. Over ten years, the HFP showed a significant increase around the urban agglomeration, in midstream and upstream towns, and near transportation networks. In 2020, the average level of HFP for the entire basin was 0.29, which increased significantly with the gradients of human activity. The HFP increased at L1, L2, and L3 gradient areas during the 10 years, although it showed a decreasing trend in L4 gradient areas. Specifically, there was a 55.99% increase in the HFP in the L1 gradient and a 1.07% decrease in the L4 gradient (Table 2).

Table 2. The average level in 2020 and the 10-year rate of change of the human footprint index in the basin and within each human activity gradient. L1–L4 represents ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas, respectively. HFP represents the human footprint index.

Time	L1	L2	L3	L4	Entire Basin
2010	0.10	0.22	0.61	0.81	0.22
2020	0.15	0.28	0.78	0.80	0.29
10-Year Change Rate	+55.99%	+28.74%	+27.37%	−1.07%	+28.83%

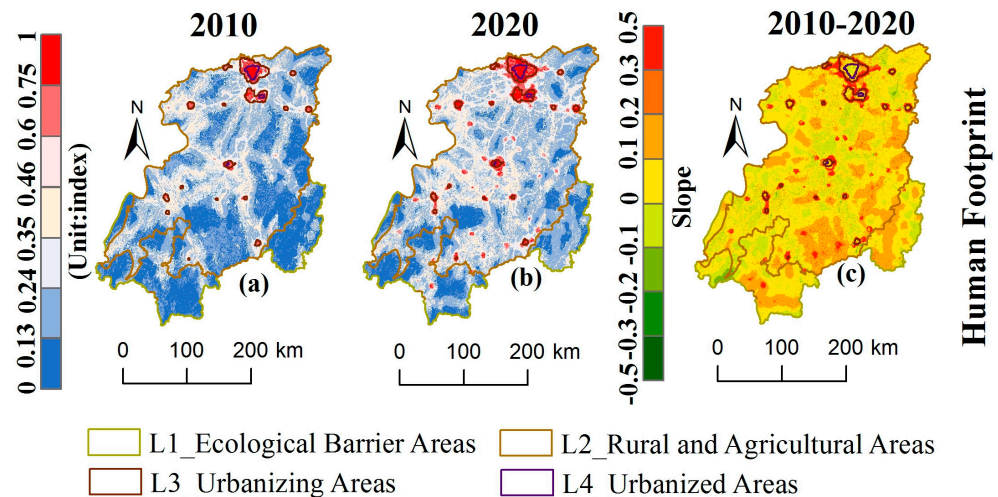


Figure 4. Spatial and temporal changes in human footprint index in Xiangjiang River Basin. (a–c) represent the spatial distribution of the human footprint index in the whole basin in 2010, 2020, and 2010–2020 slope, respectively. L1–L4 in the figure represents four different human activity gradient areas (ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas).

3.3. Correlation Between Ecosystem Services and the Human Footprint

Except for WS, the HFP exhibited a negative correlation with other ESs. As the gradient of human activities increased, the correlation coefficient between HFP and HQ, CS, WS first rose and then fell (Table 3). Among them, the HFP was negatively correlated with HQ ($r = -0.736$, $p < 0.05$) and CS ($r = -0.712$, $p < 0.05$) in the whole basin, and was positively correlated with WS ($r = 0.589$, $p < 0.05$). Within the L1 gradient areas, the HFP was negatively correlated with CS ($r = -0.621$, $p < 0.05$), while positively correlated with WS ($r = 0.515$, $p < 0.05$). Within the L2 gradient areas, the HFP was negatively correlated with HQ ($r = -0.739$, $p < 0.05$) and CS ($r = -0.722$, $p < 0.05$), while positively correlated with WS ($r = 0.579$, $p < 0.05$). Within the L3 gradient areas, the HFP was negatively correlated with HQ ($r = -0.527$, $p < 0.05$), while positively correlated with FP ($r = 0.085$, $p < 0.05$) and SC ($r = 0.028$, $p < 0.05$). Within the L4 gradient areas, the relationship between the HFP and CS was not significant. The HFP was negatively correlated with HQ ($r = -0.515$, $p < 0.05$), while positively correlated with WS ($r = 0.074$, $p < 0.05$).

Table 3. Coefficients of correlation between ecosystem services and human footprint index in the basin and the human activity gradient areas. L1–L4 represents ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas, respectively. HQ, CS, FP, SC, and WS represent habitat quality, carbon sequestration, food production, soil conservation, and water supply ecosystem service, respectively. HFP represents the human footprint index. FP had no valid values in the L1 gradient and L4 gradient. The label “***” means that the p -value in the significance test is less than 0.05.

Human Activity Gradients	HFP–HQ	HFP–CS	HFP–FP	HFP–SC	HFP–WS
L1	−0.54 **	−0.621 **	/	−0.313 **	0.515 **
L2	−0.739 **	−0.722 **	−0.091 **	−0.27 **	0.579 **
L3	−0.527 **	−0.225 **	0.085 **	0.028 **	0.248 **
L4	−0.515 **	−0.019	/	−0.176 **	0.074 **
Entire Basin	−0.736 **	−0.712 **	−0.126 **	−0.426 **	0.589 **

3.4. Non-Linear Fit Curve Between Ecosystem Services and Human Footprint

In the whole basin, as the HFP increased, HQ and CS showed a three-stage trend of “slight decrease–rapid decrease–slight decrease until stabilization”. FP slightly increased followed by a significant drop until stabilization. SC showed an exponential decline until stabilization. Also, WS showed a trend of a slight decrease followed by a slow increase until stabilization (Figure 5, Table A3). Among these, the sensitivity intervals for HQ to HFP were 0.18–0.3; for CS, 0.15–0.3; for FP, 0–0.4; for SC, 0–0.3; and for WS, 0–0.4.

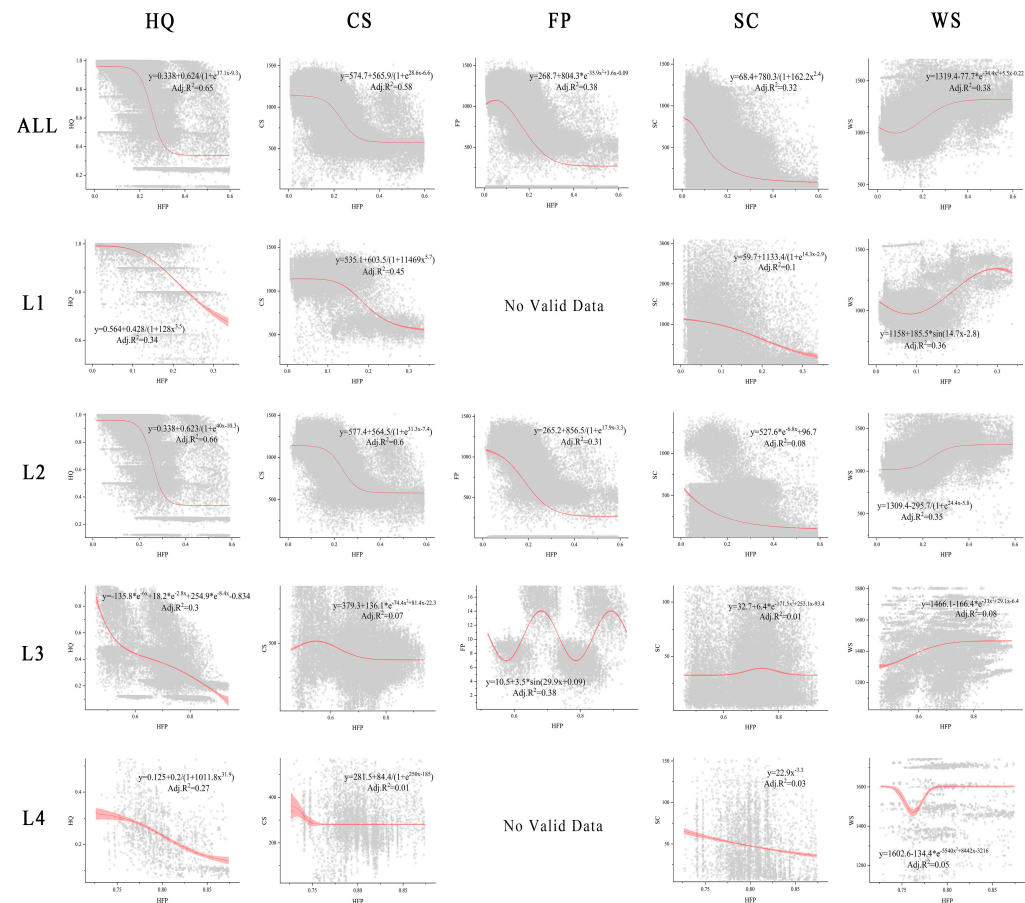


Figure 5. Nonlinear curve-fitting functions for ecosystem services and human footprints in basins and areas with various human activity gradients. The vertical coordinates of the plots of the fitted functions are ecosystem services. The horizontal coordinate of the plot of the fitted function is the human footprint index. L1–L4 represents ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas, respectively. HQ, CS, FP, SC, and WS represent habitat quality, carbon sequestration, food production, soil conservation, and water supply ecosystem service, respectively. HFP represents the human footprint index. FP had no valid values in the L1 gradient and L4 gradient.

In the L1 gradient areas, as the HFP increased, HQ and CS initially showed a slight decline before rapidly decreasing. SC exhibited a gradual decrease, and WS displayed a three-phase trend of “decrease–increase–decrease.” The sensitive interval for HQ to HFP was 0.1–0.35; for CS to HFP was 0.15–0.25; for SC to HFP was 0.1–0.3; and for WS to HFP was 0–0.35. In the L2 gradient areas, as the HFP increased, the trends of HQ, CS, FP, and WS were essentially consistent with the whole basin scale. Among them, the sensitive interval of HQ to HFP was 0.2–0.34; for CS to HFP was 0.18–0.3; for FP to HFP was 0.1–0.28; and for WS to HFP was 0.2–0.3. In the L3 gradient areas, as an increase of HFP, HQ showed an exponential decrease before gradually decreasing, while FP showed a cyclical fluctuation trend of “decrease–increase–decrease–increase–decrease”. The sensitive

interval for HQ to HFP was 0.45–0.6; while FP to HFP was 0.53–0.93. In the L4 gradient areas, HFP increased, HQ exhibited a gradual decline; the sensitive interval of HQ to HFP was 0.77–0.83.

As the HFP increased with human activity intensity, HQ responded more sensitively to the increase. CS's response to the increased HFP was consistent with the whole basin scale. FP showed a significant shift in the trend of response to the increased HFP. SC had a more subdued response to the increased HFP. WS's response to the HFP growth exhibited an initial sensitivity followed by a gradual trend. In addition, with the increase in human activities, the curve fitting between the HFP and some ESs was poor (e.g., HFP–SC in the L2 gradient; HFP–CS, HFP–SC, and HFP–WS in the L3 gradient; HFP–CS, HFP–SC, and HFP–WS in the L4 gradient, Figure 5).

3.5. Spatial Relationships Between Ecosystem Services and Human Footprint

A negative correlation between the HFP and ESs was revealed through Moran's I index (Figure 6f–j). The spatial relationship between HFP and ESs showed heterogeneity through the LISA map (Figure 6a–e). In particular, the HFP was spatially negatively correlated with HQ, CS, FP, and SC, with global Moran's I indices of -0.09 , -0.052 , -0.015 , and -0.079 , respectively. The spatial relationship between HFP and HQ was dominated by “high–low” clustering. The spatial relationships in HFP–CS and HFP–WS were dominated by “low–low” clustering. The spatial relationships in HFP–FP and HFP–SC were dominated by “low–high” clustering.

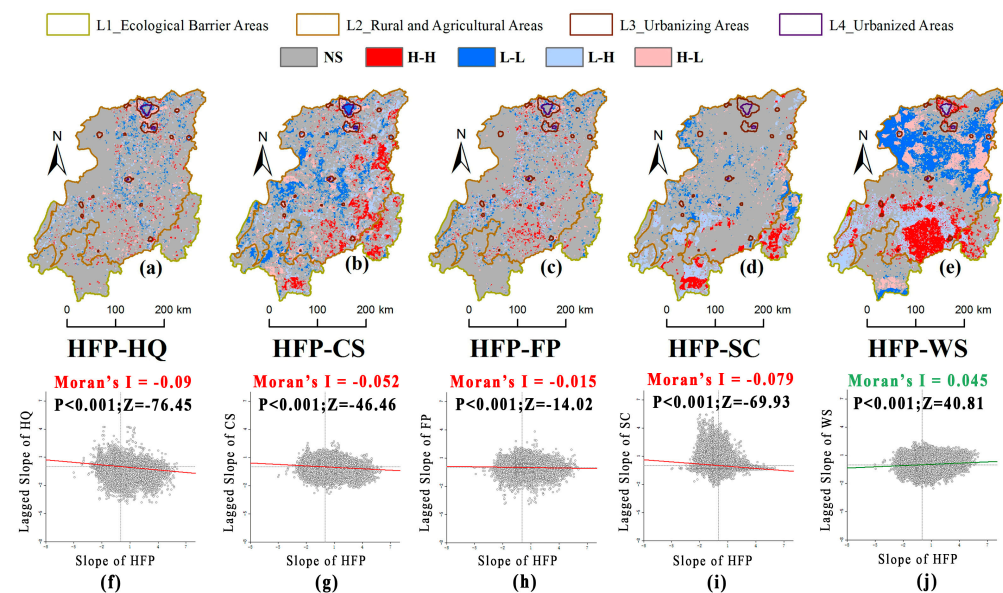


Figure 6. Map of the spatial relationship between ecosystem services and human footprint in the basin. (a–e) LISA plot of spatial relationships between HFP and HQ, CS, FP, SC, and WS; (f–j) Scatterplot of global Moran's I index between five pairs of relations. In the legend, “NS, H-H, L-L, L-H, and H-L” represent five spatial relationships (Spatial uncorrelation between HFP and ESs, “High–high” spatial clustering of HFP and ESs, “Low–low” spatial clustering of HFP and ESs, “Low–high” spatial clustering of HFP and ESs, “High–low” spatial clustering of HFP and ESs). L1–L4 represents ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas, respectively. HQ, CS, FP, SC, and WS represent habitat quality, carbon sequestration, food production, soil conservation, and water supply ecosystem service, respectively. HFP represents the human footprint index. FP had no valid values in the L1 gradient and L4 gradient.

The spatial relationship of “high–low” clustering showed a significant downward trend in ES with an increase in the HFP, which is not conducive to the sustainable development of the basin. Therefore, we analyzed the distribution of “high–low” clusters among five pairs of spatial relationships (Table 4). The results showed that in the whole basin, the areas occupied by “high–low” clusters between HFP and HQ made up 4.32%, while that between HFP and FP accounted for 3.06%. Both were mainly in the lower part of the basin around the urban agglomeration. The “high–low” clustering areas of HFP–CS accounted for 7.64%, with scattered patches in the upper, middle, and lower reaches of the basin. The “high–low” clustering areas of HFP–SC accounted for 2.28%, with scattered distributions on both the east and west sides in the middle reaches. The “high–low” clustering areas of HFP–WS accounted for 10%, with extensive patchy distribution in the transition areas of the middle and lower reaches of the basin. Under different human activity intensities, HFP–CS trade-off relationships were dominant in the L1 and L2 gradients, accounting for 1.10% and 1.07% of the basin. HFP–WS trade-off relationships were dominant in the L1 and L2 gradients, accounting for 5.29% and 8.80% of the basin areas, respectively. While the HFP–CS trade-off dominated in the L3 and L4 gradients, accounting for 1.24% and 0.01%.

Table 4. Percentage of the area in the basin and human activity gradient areas with “high–low” clustering type in five pairs of spatial relationships. L1–L4 represents ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas, respectively. HQ, CS, FP, SC, and WS represent habitat quality, carbon sequestration, food production, soil conservation, and water supply ecosystem service, respectively. HFP represents the human footprint index.

Human Activity Gradients	HFP–HQ	HFP–CS	HFP–FP	HFP–SC	HFP–WS
L1	0.13%	1.10%	0.30%	0.47%	1.07%
L2	3.25%	5.29%	2.26%	1.79%	8.80%
L3	0.93%	1.24%	0.50%	0.02%	0.13%
L4	<0.01%	0.01%	<0.01%	0%	0%
Entire Basin	4.32%	7.64%	3.06%	2.28%	10.00%

4. Discussion

4.1. Differences in the Spatial and Temporal Distribution of Ecosystem Services and Human Footprint

Different land use and cover types not only provide a variety of ESs but undergo modification and destruction because of human demands and social development [50]. In this study, built-up land and cropland showed high levels on the HFP, while forest land and grassland exhibited high levels of ES supply (Table A4). Specifically, built-up land in the L4 gradient areas exhibited the highest level of WS. This may be because impervious surfaces in built-up land affected water infiltration, leading to increased surface runoff. As an urban basin, high water yield from built-up land was also found in the study of the Chaobai River basin by Li et al. [51]. Some scholars have found that there is a gradient effect of urbanization on ecosystems in mountain landscapes [52]. Future efforts should focus on the “sponge city” to enhance the capacity to resist flood disasters and set up risk prevention zones by identifying different gradients. Additionally, the highest levels of HQ, CS, and SC exhibited in the L1 gradient areas, and had the highest proportion of forest land and favorable ecological conditions. This corresponded with the findings of Zhou et al. [37] in assessing the value of ESs in the Xiangjiang River Basin. Meanwhile, we also found that the HFP increased by 55.99% in the L1 gradient areas over 10 years. This showed that ecological barrier zones were experiencing increasing environmental pressure from human activities. Future efforts should emphasize the construction of protected areas, strictly controlling the intensity of human activities within these areas. In addition, cropland, which is the second largest land use type in the HFP, occupies 27.7% of the total area (Table A4, Figure 1). This may result in the basin environment being affected by non-point source pollution and

water consumption [33]. Future research should focus on the middle reaches of the basin to analyze the impact mechanisms of different agricultural management practices.

The impact of urban development on the environment results from multiple factors, such as population, geographic location, socio-economics, and government policies [53]. This study found that CS in the L4 gradient areas increased nearly twofold over the decade (97.45%, Figure 3). The increasing demand for urban environment quality with society development has led to a greater emphasis on designing “blue-green space” within cities. This was achieved by increasing urban green space in densely populated areas to enhance human well-being. For instance, Changsha, a core city within the basin, has been actively responding to China’s Ministry of Housing and Urban–Rural Development’s “pocket park” policy (https://www.gov.cn/zhengce/zhengceku/2022-08/09/content_5704766.htm, accessed on 5 May 2023). By expanding urban green spaces since 2020, Changsha has built over 130 “pocket parks” with areas ranging from 400m² to 10000m² (<https://www.hunantoday.cn/news/xhn/202208/16717127.html>, accessed on 5 May 2023). In addition, this study also found that the HFP decreased in the L4 gradient areas over the decade (−1.07%, Table 2). This indicated that urbanization in the areas had reached a certain level, and the intensity of human activities had slowed down, marking the onset of “counter-urbanization” [54]. This may be attributed to the saturation of land utilization in the core urban areas with rapid economic development. Consequently, some industries and populations had migrated to the periphery of the city, such as the urbanizing regions in the L3 gradient. This aligned with the policy backgrounds of collaborative development regions like the Changsha–Zhuzhou–Xiangtan urban agglomeration [55] and the Xiangjiang River Basin Economic Belt [34]. Future research should explore sustainable urban development models that harmonize socio-economics and natural ecosystems by integrating studies on human well-being and urban planning.

4.2. Response of the Relationship Between Ecosystem Services and Human Footprint Under Human Activity Gradients

Ecosystem services act as a bridge between natural ecosystems and socio-economics, influenced by multiple factors such as natural disturbances and human activities [56]. Our study suggested that the relationship between ESs and HFP became more complex as the intensity of human activity increased. First, as the human activity gradients increased, the correlation coefficient of ESs and HFP showed a decrease, a shift in the correlation, or became non-significant (Table 3). This may be because of the more diverse environmental pressures within high human activity gradient areas, making the impact mechanisms on ESs more complex. As a comprehensive index, the HFP was limited to analyzing more complex and specific impact mechanisms. Second, the nonlinear curve fitting results showed that the fitting accuracy of HFP–ES decreased, and some HFP–ES response curve trends changed significantly as human activity increased (Figure 5). This further showed that the response mechanism of ES to HFP became more complex as human activity gradients increase, which was also corroborated by the results of the correlation analysis (Table 3). We also found the same pattern in Pan et al.’s study [57], by drawing ecological Kuznets curves to compare and analyze the relationship between ES value and gross domestic product (GDP) under four gradients: national, ordinary city, urban agglomeration, and core city. They found that with increasing urbanization intensity, the form of the Kuznets curve becomes more complex, showing a significant shift compared to the national scale trend. However, Liu et al.’s study on the Yangtze River Basin found that the response of ES values to human activity pressures was more stable in urbanized areas than in non-urbanized areas [26]. This may be related to the ES value assessment method [58], which calculated the total value of all ecosystem services provided by different land use types within the area. However, the land use transformation is strictly controlled in China because of land use policy [59]. Hence, ES values within the urban areas show higher stability. Therefore, future research in urban areas should refine the human activity types and quantitative

indicators for different ESs, analyzing the complex relationship between human activities and specific ESs by constructing a driving factors system.

Our results showed that the response of different ESs to HFP varies. Initially, the response curve of HQ to HFP showed a trend of “slight decline followed by rapid drop” in the L1 and L2 gradients, and a rapid decline in the L3 and L4 gradients (Figure 5). This may be because of the “ecological resilience” [60] of ecosystems. When facing environmental pressures, ecological barrier areas, rural and agricultural production areas, which were dominant in forest land, showed a better performance on environmental carrying capacity [61]. However, when environmental pressure exceeded a certain “threshold”, HQ underwent a sharp decline, as observed in the urbanized areas of this study. Second, in the L3 gradient areas, the response curves of FP and HFP differed from the other gradients, showing a cyclic fluctuation trend. This may be related to the location of the transition region from the L2 gradient to the L3 gradient. In this transition region, there may be a spatial distribution of “agricultural production areas–urbanizing areas–peri-urban agricultural areas–urbanized areas”. This was well fitted with the “concentric zone theory” proposed by the German agricultural economist von Thunen in 1826 [62]. Additionally, with the increase in gradients, the response of CS to HFP remained relatively stable within the range of 0.15–0.3, showing a trend of slight decline followed by a sharp drop and then returning to stability on the response curve. This might be because CS, among the many ESs, exhibited higher stability when facing increased environmental pressures [63], and hence a lag in response to the human footprint. This result was consistent with the findings in the Yangtze River Basin, where Liu et al. reported a decreasing trend in ES values with increasing human activities, both in urbanized and non-urbanized areas [26]. However, studies in the Lhasa River Basin presented inconsistent results. Han et al. analyzed the effects of WS, SC, CS, and HQ on the Lhasa River Basin in response to human activities [64]. They found that WS and SC showed an exponential decrease with the increase in human activities, while CS and HQ exhibited, at first, an increasing trend, followed by a decreasing trend. These differences may relate to the characteristics of the Lhasa River Basin. The basin is on the Tibetan Plateau and has abundant water resources and few impervious surfaces, making WS particularly sensitive to increased human activities. In recent years, implementing ecological projects in the basin has protected and improved grassland ecosystems, which contributed the most to CS [65], and enhanced the HQ for species [66]. Therefore, appropriate and positive human interventions can enhance the provision of ESs in basins oriented towards ecological protection.

4.3. Limitations

The impacts of human activities on natural ecosystems are profound, with the complexity arising from different types and intensities of human activities [58]. This study found some limitations of the human footprint index in resolving the complex relationship between ESs and HFP. Future studies should construct a more specific system of driving factors in urban agglomeration scale research. Because of limited data availability, this study only collected data for two time slices. Various ecological models quantified multiple ESs and the HFP, which might introduce uncertainties in the analysis results. Therefore, future research should extend the temporal scope and collect more measured data to enhance the precision of assessment results.

In addition, the “high–low” clustering areas of HFP–ESs were mainly in the middle and lower reaches, which were not conducive to the synergistic development of nature and society [67]. Therefore, further sample studies in these areas are necessary. In recent years, ecological compensation policies have been crucial measures for improving ecological environment quality and regional synergistic development [68]. For this reason, we could explore some policy suggestions for ecological compensation mechanisms in upstream and downstream regions of the basin in the future. This will further advance the sustainable development of the socio-ecological coupled system.

5. Conclusions

In this study, we analyzed the spatial and temporal distribution characteristics of the HFP and five ESs in the Xiangjiang River Basin from 2010 to 2020 using multi-source remote sensing data. We also examined the relationship between HFP and ESs under different human activity intensities. The results showed that: (1) From 2010 to 2020, HQ and WS in the basin decreased by 4.59% and 16.49%, respectively. However, the other ESs showed an increasing trend. The upper hilly areas had higher ES levels. The magnitude of changes in the four ESs, except WS, enhanced with increasing human activity. (2) HFP increased by 28.83% over the 10 years and was distributed in point and patchy clusters in the valley plains of the lower and middle reaches. HFP increased significantly with increasing human activity gradients. (3) In terms of quantitative characteristics, there was a significant positive correlation between HFP and WS, and a significant negative correlation with the other ESs. In particular, ESs were most sensitive to the HFP within the 0–0.4 interval. As the intensity of human activities increased, the correlation between HFP and ESs weakened, and the response curves of ES to HFP became more volatile. (4) Regarding spatial characteristics, the spatial correlation of HFP–ESs were consistent with the quantitative characterization results. The spatial relationship was primarily manifested as “high–low” clustering and “low–high” clustering, distributed in the lower-middle reaches and the upper reaches, respectively. HFP–CS “high–low” clustering areas dominated as the human activity gradients increased. In summary, this study found that some ESs and the HFP increased in the Xiangjiang River Basin over 10 years. The relationship between HFP and ESs were primarily negative, spatially manifested as “high–low” clustering and “low–high” clustering trade-offs. Different ESs were sensitive to HFP in response to specific intervals, and the relationship between HFP and ESs was more complex with increasing human activity gradients. This study deciphers the relationship between HFP and ESs across multiple scales. It also aids our understanding of how ESs respond to the HFP under various levels of human activity. Finally, it provides important scientific support for sustainable socio-ecological development and ecosystem management in the basin.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1. List of data sources.

Data Types	Datasets	Sources	Spatial Resolution	Time
Land use data	Land use	GlobeLand30	30 m	2010/2020
Soil data	Soil maximum root depth	Resource and Environment Data Center of the Chinese Academy of Sciences	1 km	—
	Soil available water	World Soil Information Data Platform	250 m	—
	Soil particle size	HWSD	1 km	—
Evapotranspiration data	Potential evapotranspiration	MOD16A2GF	500 m	2010/2020
Vegetation data	Normalized difference vegetation index	MOD13Q1	250 m	2010/2020
Topographic data	Digital elevation model	ASTERGDEM	30 m	—
Meteorological data	Precipitation	National Meteorological Science Data	—	2010/2020
	Average temperature	Center Near-surface Meteorological Observations Dataset	—	2014/2020
	Solar radiation	OpenStreetMap	—	2014/2020
Human activities data	Traffic network	Global NPP-VIIRS-like Nighttime Light Data	500 m	2010/2020
	Nighttime light index	Hunan Provincial Bureau of Statistics	—	2011/2021

Table A2. Proportion of land-use types in areas with different human activity gradients. L1–L4 in the table represents four different human activity gradient areas (ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas).

Human Activity Gradients	Cropland	Forest Land	Grassland	Wetland	Water Area	Built-Up Land	Unused Land
L1	13.48%	73.97%	10.51%	0%	1.23%	0.81%	0.01%
L2	32.14%	54.44%	9.03%	0.01%	1.71%	2.65%	0.01%
L3	16.49%	18.95%	4.28%	0.11%	6.80%	53.37%	0%
L4	1.10%	8.22%	0.82%	0.27%	7.95%	81.64%	0%
Entire Basin	27.74%	57.69%	9.22%	0.01%	1.73%	3.60%	0.01%

Table A3. Nonlinear curve-fitting functions for ecosystem services and human footprints in basins and areas with various human activity gradients. L1–L4 represents ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas, respectively. HQ, CS, FP, SC, and WS represent habitat quality, carbon sequestration, food production, soil conservation, and water supply ecosystem service, respectively. HFP represents the human footprint index. FP had no valid values in the L1 gradient and L4 gradient.

Curve-Fitting Functions	HQ-HFP	CS-HFP	FP-HFP	SC-HFP	WS-HFP
L1	$y = 0.564 + 0.428 / (1 + 128 \times 3.5)$	$y = 535.1 + 603.5 / (1 + 11469 \times 5.7)$	No Valid Data	$y = 59.7 + 1133.4 / (1 + e^{14.3x - 2.9})$	$y = 1158 + 185.5 \sin(14.7x - 2.8)$
L2	$y = 0.338 + 0.623 / (1 + e^{40x - 10.3})$	$y = 577.4 + 564 / (1 + e^{31.3x - 7.4})$	$y = 265.2 + 856.5 / (1 + e^{17.9x - 3.3})$	$y = 527.6e^{-6.8x} + 96.7$	$y = 1309.4 - 295.7 / (1 + e^{24.4x - 5.8})$
L3	$y = -135.8e^{-6x} + 18.2e^{-2.8x} + 254.9e^{-8.4x} - 0.834$	$y = 379.3 + 136.1e^{-74.4x^2 + 81.4x - 22.3}$	$y = 10.5 + 3.5 \sin(29.9x + 0.09)$	$y = 32.7 + 6.4e^{-171.5x^2 + 253.1x - 93.4}$	$y = 1466.1 - 166.4e^{-33x^2 + 29.1x - 6.4}$
L4	$y = 0.125 + 0.2 / (1 + 1011.8 \times 31.9)$	$y = 281.5 + 84.4 / (1 + e^{250x - 185})$	No Valid Data	$y = 22.9x^{-3.3}$	$y = 1602.6 - 134.4e^{-5540x^2 + 8442x - 3216}$
Entire Basin	$y = 0.338 + 0.624 / (1 + e^{37.1x - 9.3})$	$y = 574.7 + 565.9 / (1 + e^{28.6x - 6.6})$	$y = 268.7 + 804.3e^{-35.9x^2 + 3.6x - 0.09}$	$y = 68.4 + 780.3 / (1 + 162.2 \times 2.4)$	$y = 1319.4 - 77.7e^{-34.4x^2 + 5.5x - 0.22}$

Table A4. Average levels of ecosystem services and human footprint index within each land use cover type. L1–L4 in the table represents four different human activity gradient areas (ecological barrier areas, rural and agricultural areas, urbanizing areas, and urbanized areas). HQ, CS, FP, SC, and WS represent five ecosystem services (habitat quality, carbon sequestration, food production, soil conservation, and water supply). HFP represents the human footprint index.

Human Activity Gradients	HQ Index	CS $\text{gC}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$	FP t	SC $\text{t}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$	WS mm	HFP Index
FCropland	0.24	558.18	18.08	134.67	1326.90	0.38
Forest Land	0.96	1119.45	0	471.32	1059.67	0.17
Grassland	0.74	594.52	0	177.20	1271.05	0.30
Wetland	0.79	370.64	0	19.53	1091.97	0.37
Water Area	0.44	415.55	0	96.94	1126.61	0.28
Built-up Land	0	378.56	0	82.44	1529.15	0.50
Unused Land	0	562.91	0	114.95	1425.24	0.13

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