The impacts of urban land expansion on ecosystem services in Wuhan, China

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Abstract

A clear understanding of the impacts of urban land expansion on ecosystem services is crucial for sustainable urban planning. Although various studies have shown that urban land expansion caused a degradation of ecosystem services, the relationship between the spatial variation of urban land expansion and ecosystem services still remains unclear. This study quantified the ecosystem services and urban land expansion indicators of Wuhan for 1990–2015 and analyzed the spatial and temporal variation characteristics of ecosystem service values (ESVs) and urban land expansion indicators. Using spatial autocorrelation analysis and linear regression, the quantitative and qualitative correlations between ecosystem services and urban land expansion indicators were explored. The total ESV of Wuhan decreased by 16.47%, representing a loss of 1636.19 million yuan. Areas with extremely low ESVs continuously expanded outward from the urban center. During 2010–2015, the urban land expansion area, intensity, damage weight, and distance peaked, which caused an enormous decrease of the total ESV. Negative correlations were found between urban land expansion and all ecosystem services; the correlation with food production was most significant, indicating that urban land expansion had the strongest impact on food production. The expansion area is the main factor causing the decline of each ecosystem service among urban land expansion indicators. This study presents the impact characteristics of urban land expansion on ecosystem services, and the results provide a reference for reasonable decision making in urban planning.

Keywords Ecosystem services · Urban land expansion · Spatial and temporal variations · Spatial autocorrelation · Linear regression analysis · Wuhan

Introduction

Ecosystems are the life-support systems of the Earth and provide resources for human survival and the development of society (Luo and Zhang 2014). The goods or services human beings can directly or indirectly obtain from ecosystems are called ecosystem services (Costanza et al. 1997). In 2005, the Millennium Ecosystem Assessment assessed the global ecosystem services and their impacts on human well-being with multiple scales and reported that 60% of ecosystem services showed a decreasing trend (MEA 2005). Human activities are the main force leading to structural changes and the decline of ecosystem services (Han et al. 2020; Ning et al. 2015), among which, the impacts of land use/cover change (LUCC) on ecosystem services are particularly prominent (Abulizi et al. 2016; Chen et al. 2017; Li and Zhou 2015; Thomas and Roland 2013). Costanza et al. (2014) estimated that the loss of ecosystem services because of land use change during 1997 to 2011 reached $4.3–20.2 trillion/year in 2007 $US.

Urban land expansion is the mainly and most intense LUCC of urbanization (Liu et al. 2016), and China has experienced particularly extensive and rapid urban land expansion. From 1990 to 2015, urban land in China increased by 311.4% (Wang and Lu 2018). The urban land expansion includes many other land-use types, thus endangering regional ecological security (Fu et al. 2017; Xie et al. 2019) and causing air pollution (Zhao et al. 2006) and water pollution (Ren et al. 2014), threatening biodiversity (Seto et al. 2011), affecting ecosystem productivity (Seto et al. 2012), exerting

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tremendous pressure on ecosystems, and destroying ecosystem services (Lin et al. 2013). Therefore, coordinating the relationship between urban land expansion and the ecosystems as well as reducing the impacts of urban land expansion on the ecosystems is of great significance for urban planning decisions, especially for areas undergoing rapid urbanization.

The impacts of LUCC on ecosystems can be measured in monetary form by the ecosystem service value (ESV). Many scholars and researchers have focused on the relationship between LUCC and ecosystem services, thus identifying the rules and mechanism underlying the impacts LUCC have on ecosystem services (Solomon et al. 2019; Wang et al. 2017; Yuan et al. 2019). A number of scholars have also preliminarily explored the impacts of urban land expansion on ecosystem services. For instance, Su et al. (2014) calculated the dynamic changes of ESVs in Shanghai, China, and described the relationship between these ESV changes and urbanization. Zhang et al. (2018) integrated population density and GDP density into the index of urban land expansion to explore the spatial relationship between urbanization and ecosystem services. Wang et al. (2020) calculated the speed of urban land expansion and assessed the impacts of urbanization on ecosystem services change. Xie et al. (2018) projected the historical and potential impacts of urban land expansion on the main set of ecosystem services. Hu et al. (2017) and Meng (2016) analyzed the urban area and ESV through correlation analysis and quantified the impacts of urban land expansion on ESV. However, these studies either regarded urban land expansion as one of the indicators of urbanization or only considered the temporal changes of ecosystem services. The impacts of spatial indicators (slope, elevation, and distance) of urban land expansion on ecosystem services have not been explored to date, and therefore, the impacts of urban land expansion on ecosystem services cannot be fully understood.

The urban land and population of Wuhan, an important city in Central China, increased significantly over recent years, and the associated drastic change of land use cover caused severe environmental problems. The study selected Wuhan and explored the impacts of urban land expansion on ecosystem services from both spatial and temporal perspectives. The objectives of this study are to (1) calculate the ESVs and analyze both the spatial and temporal dynamic characteristics of ESV changes, (2) comprehensively explore the variations of urban land expansion indicators during the study period, (3) analyze the direct spatial correlation between urban land expansion and ecosystem services, and (4) quantify the impacts of urban land expansion indicators on ecosystem services. Specifically, spatial autocorrelation analysis and linear regression model were introduced to explore the qualitative and quantitative correlations of urban land expansion and ecosystem services. The results provide a reference for urban planning decision-makers for the coordination of urban land

expansion and ecosystem services and for promoting the sustainable development of developing cities.

Materials and methods

Study area

Wuhan is the capital of Hubei Province, China. Wuhan is located in the east of Hubei, between 29° 58′–31° 22′ N latitude and 113° 41′–115° 05′ E longitude (Fig. 1). The total area is approximately 856,915 hm^2. The overall relief is high in the north and low in the south, and the topography is dominated by undulating hills and plains. Wuhan is situated at the intersection of the Yangtze River and the Hanjiang River, with numerous lakes and a developed water system within the area.

With the implementation of the strategy of the "Rise of Mid-China," the scale of industrial agglomeration in Wuhan gradually increased, the process of urbanization continued to accelerate, and Wuhan has developed into one of the core regions of Central China (Du et al. 2010; Gui et al. 2019; Zhang et al. 2020). The process of rapid urbanization not only expands the scales of economy and population, but also leads to a drastic evolution of land spatial pattern. Moreover, affected by resource exploitation, industrial construction, and the expansion of urban land, the ecological space is seriously occupied. This causes serious problems of environmental degradation, inefficient resource utilization, and an imbalanced urban and rural development (Chen et al. 2020; Jun et al. 2017). Ecosystem services are greatly affected.

Data collection

The main data used in this study include (1) land use and elevation data of Wuhan for 1990, 1995, 2000, 2005, 2010, and 2015, sourced from the Resource and Environment Science and Data Center of China (http://www.resdc.cn); (2) net primary synthesis (NPP) data was sourced from the National Earth System Science Data Center of China (http://www.geodata.cn) and the Resource and Environment Science and Data Center of China (http://www.resdc.cn); (3) Wuhan's grain output per unit area was sourced from the *Wuhan Statistical Yearbook*; (4) the value of agricultural product income was sourced from the *Compilation of cost and benefit information of agricultural products in China*.

Methods

Four steps were applied: (1) ESV categories and services were calculated, (2) the indicators of urban land expansion were quantified, (3) the correlation between urban land expansion and ecosystem services was explored through spatial autocorrelation, and (4) the multiple linear regression method was
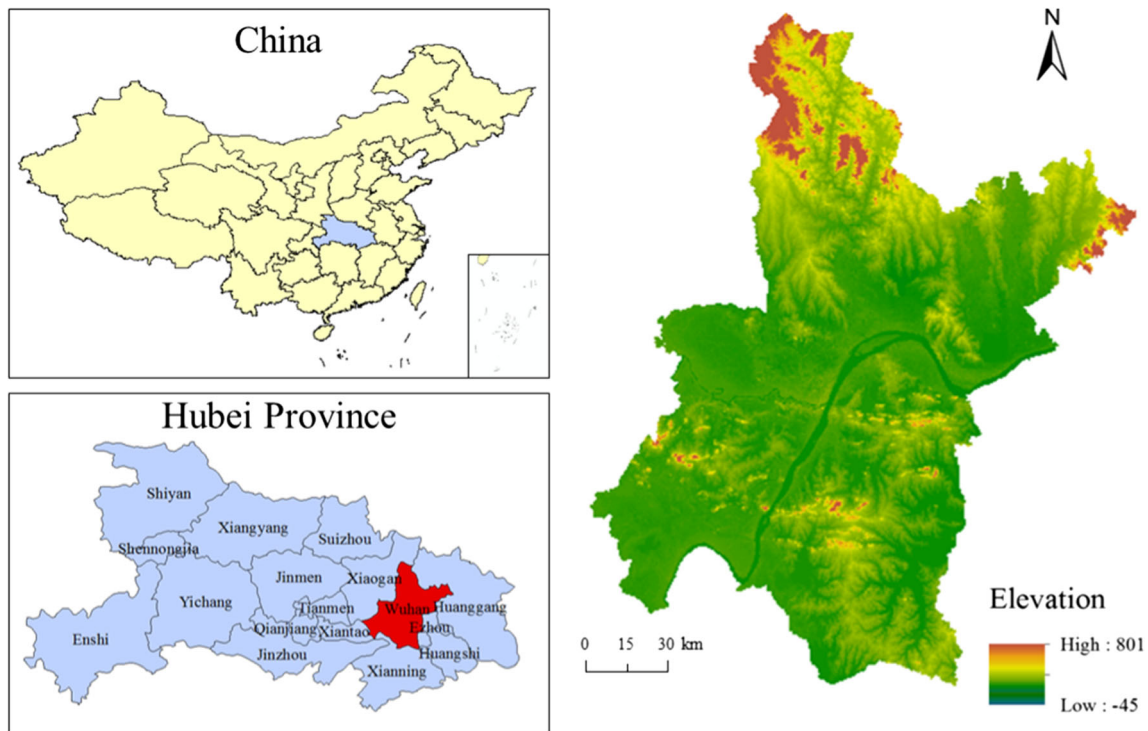
Fig. 1 Location of Wuhan City in Hubei Province, China

used to quantitatively analyze the impacts of urban land expansion on ecosystem services.

Calculation of ecosystem service values

This study used the results of Costanza et al. (1997) and Xie et al. (2008) as foundation. In 1997, Costanza et al. (1997) estimated the economic values of 17 ecosystem services per unit by biome, and multiplied these values by the total area of each biome, summed over all services and biomes. This approach defined a framework for the calculation of ESVs, which significantly influenced further studies of ecosystem services. However, this framework mainly reflected the economic development level of developed countries, as because of the gap of ecological environment and socio-economic development between China and developed countries, direct application of the model does not enable the effective and accurate estimation of the ESVs of China. To resolve this problem, Xie et al. (2008) improved the model based on China's ecological environment and economic development and calculated the equivalent value per unit area of nine ecological services in China (Table 1). An evaluation system suitable for China was formed and widely applicated (Chen et al. 2016, 2019; Geng et al. 2020).

The value of one standard equivalent value per unit area equals to 1/7 of the economic value of the grain production per unit area of cropland (Xie et al. 2008). Because of the dynamic

temporal changes of ESVs (Liu et al. 2018), the equivalence value was revised according to the time value of currency to eliminate the influence of economic factors such as inflation. The relevant formulas are presented in the following:

$$D_j = 1/7 \sum_{l=1}^{n} V_{lj} \tag{1}$$

$$D_{Tj} = D_j + D_j \times \sum_{m=j}^{2014} \gamma_m \tag{2}$$

where D_j and D_{Tj} represent the value of one equivalent value per unit area before and after the temporal correction in year j (yuan/hm^2), respectively; V_{lj} represents the average production value contributed by the l-type crop in year j in Wuhan (yuan/hm^2); and γ_m represents the fixed rate of the bank in year m (%).

Usually, the net primary synthesis (NPP) can reflect the capacity of ecosystem services (Liu et al. 2018). Therefore, the ratio of the NPP per unit area of each block to the average NPP per unit area of the ecosystem which obtains the block was used as correction coefficient, and ESVs were revised on the micro-spatial scale by blocks. The formula of the correct factor is shown in the following:

$$\alpha_{ij} = NPP_{ij}/\overline{NPP}_{ij} \tag{3}$$

where α_{ij} represents the correction coefficient of block i in year j; NPP_{ij} represents the NPP value per unit area of block i in year j; and $\overline{NPP}_{ij}$ represents the average NPP value per unit

Table 1 Equivalent values per unit area of ecosystem services in China

Services	Provision		Regulating				Supporting		Culture
Sub-services	FP	RMP	GR	CR	HR	WT	SC	BM	AL
Farmland	1.00	0.39	0.72	0.97	0.77	1.39	1.47	1.02	0.17
Forestry land	0.33	2.98	4.32	4.07	4.09	1.72	4.02	4.51	2.08
Grassland	0.43	0.36	1.50	1.56	1.52	1.32	2.24	1.87	0.87
Wetland	0.36	0.24	2.41	13.60	13.44	14.40	1.99	3.69	4.69
Dessert	0.02	0.04	0.06	0.13	0.07	0.26	0.17	0.40	0.24
Water body	0.53	0.35	0.51	2.06	18.77	14.85	0.41	3.43	4.44

Sourced from: Xie et al. (2008)

FP food production, *RMP* raw material production, *GR* gas regulation, *CR* climate regulation, *HR* hydrology regulation, *WT* waste treatment, *SC* soil conservation, *BM* biodiversity maintenance, *AL* aesthetic landscape

area.

Thereafter, the following formula was used to calculate ESV:

$$\mathrm{ESV}_{jk} = \sum_{i=1}^{n} \left(F_{ik} \times D_{Tj} \times \alpha_{ij} \times S_{ij} \right) \quad (4)$$

where ESV_{jk} represents the value of the k-type ecosystem service in the year (yuan); F_{ik} represents the equivalent value per unit area of the k-type ecosystem service in block i; and S_{ij} represents the area of block i in year j (hm^2).

Urban land expansion analysis

The quantitative analysis indicators of urban land expansion include the area, speed, and intensity of the expansion. Moreover, as urban land encroachment on diverse land-use categories causes different impacts on ecosystem services (Zhang and Kong 2011), it is necessary to define weights according to the relative importance of different ecosystem services of varying land-use categories. Hence, an expansion damage weight was introduced. Usually, the equivalent value per unit area of ecosystem services reflects the relative contribution of each service contributed by different land-use types (Xie et al. 2008). Therefore, the equivalent value per unit area was used to endow the damage weight and the NPP value was assigned to modify both spatial and temporal discrepancies among different blocks of the same land-use category. The expansion damage weight indicates the proportional change of different land-use categories occupied by urban land expansion (e.g., the increase of the expansion damage weight on food production indicates an increased proportion of farmland occupied by urban land). The sum of the damage weight on various ecosystem services is the comprehensive damage weight of urban land expansion. The formulae of these indicators are shown in the following:

$$S_{j\mathrm{new}} = S_{j+5} - S_j \quad (5)$$

$$SR_j = S_{j\mathrm{new}}/S_j \times 100\% \quad (6)$$

$$SI_j = S_{j\mathrm{new}}/S \times 100\% \quad (7)$$

$$\beta_{ij} = \mathrm{NPP}_{ij}/\overline{\mathrm{NPP}_\iota} \quad (8)$$

$$\mathrm{UGD}_{jk} = \frac{\sum_{i=1}^{n} \left(F_{ik} \times S_{ij} \times \beta_{ij} \right) - \sum_{l=1}^{m} \left(F_{lk} \times S_{l(j+5)} \times \beta_{l(j+5)} \right)}{\sum_{i=1}^{n} S_{j\mathrm{new}} - \sum_{l=1}^{m} S_{l(j+5)}} \quad (9)$$

where S represents the total area of Wuhan (hm^2); $S_{j\mathrm{new}}$ represents the urban land expansion area from j to $j + 5$ (hm^2); SR_j represents the urban land expansion rate ; S_{ij} represents the urban land expansion intensity; β_{ij} represents the correction coefficient of block i in year j; $\overline{\mathrm{NPP}_i}$ represents the average NPP of the land type where block i is located; and UGD_{jk} represents the damage value of urban land expansion in year j.

The spatial analysis of urban land expansion includes distance analysis, elevation analysis, and slope analysis. The geometric center of Wuhan's urban land in 1990 was taken as origin, with a 1-km interval as buffer zones. The blocks are numbered according to the distance between the buffer zone and the center of Wuhan.

Spatial autocorrelation analysis

Exploratory spatial data analysis (ESDA) was used to qualitatively analyze the characteristics of the spatial and temporal impacts urban land expansion had on ESVs. The core was to measure and test the spatial association pattern through spatial autocorrelation analysis (Ma and Pei 2010). To investigate spatial correlations, bivariate spatial autocorrelation analysis was employed, which was divided into global spatial autocorrelation analysis and local spatial autocorrelation analysis.

The global spatial autocorrelation analysis can identify the average degree of association and spatial distribution between the overall attributes of a region and can also reflect the similarity between each regional unit and its neighbor regional units in the whole study area. *Bivariate Moran's I* was used to explore the global spatial autocorrelation. The formula of

bivariate Moran's I is presented in the following (Anselin 1995):

$$I^i_{pq} = \frac{Y^i_p - \overline{Y_p}}{S^2_p} \cdot \sum^n_{j=1} W_{ij} \cdot \frac{Y^i_q - \overline{Y_q}}{S^2_q} \tag{10}$$

where I^i_{pq} represents the spatial correlation of both p-attribute and q-attribute on the i-th spatial unit; Y^i_p represents the p-attribute value on the i-th spatial unit; $\overline{Y_p}$ represents the average value of p-attribute values of all spatial elements in the study area; S^2_p represents the variance of p-attribute of all spatial units in the study area; W_{ij} represents the weight matrix based on row standardization; and n represents the number of all spatial units.

Local spatial autocorrelation statistical analysis was used to identify the spatial association patterns that might exist in different spatial locations. Then, the distribution characteristics of the local space were identified. Generally, *local Moran's I* was used to analyze the local spatial autocorrelation. LISA cluster maps of local spatial autocorrelation were potted on the basis of Z test ($P < 0.05$), and five types of spatial clusters were obtained: high–high cluster (HH; where the attribute values of observation areas and their surrounding areas are both high values); low–low cluster (LL; where the attribute values of observation areas and their surrounding areas are both low values); low–high cluster (LH; where the values of the observation areas are low while they are high for surrounding areas); high–low cluster (HL; where the values of the observation areas are high while they are low for surrounding areas); and not significant (NS; which indicates no spatial autocorrelation). The formula of the local Moran's I is presented in the following:

$$I_i = \frac{Y_i - \overline{Y}}{S^2_i} \cdot \sum^n_{i=1, j \neq i} W_{ij} \cdot \left(Y_i - \overline{Y} \right) \tag{11}$$

ArcGIS 10.2 and the GeoDa software (V1.6.7) were employed to map the spatial distribution characteristics of ESV and urban land expansion. Grids with an area of 5 × 5 km were constructed based on the Fishnet function of ArcGIS 10.2, and thus, Wuhan was broken up into 412 spatial units. The area of urban land in each of these spatial units was taken as the index of urban spatialization, and then, bivariate spatial analysis of ESVs and urban land expansion was carried out through the GeoDa software (V1.6.7).

Linear regression analysis

To further quantitatively analyze the impacts on ecosystem services caused by urban land expansion, multivariate linear stepwise regression analysis and significant testing were adopted to eliminate insignificant variables and construct optimal regression equations. The actual influence of each factor on ecosystem services was reflected by the nonstandard coefficient of each equation, and the influence degree was reflected by the standardization coefficient.

Results

Temporal changes in ecosystem service values of Wuhan

Changes in ecosystem service values of different land-use categories

Wuhan underwent a continuing decline of total ESV during the study period (Table 2), and the total ESV of Wuhan decreased by a total of 16.47% from 1990 to 2015, representing a loss of 1636.19 million yuan. The reduction rates of the total ESV of Wuhan City were 2.40%, 3.41%, 1.72%, 3.37%, and 6.66% for 1990–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2015, respectively. The highest reduction rate was found in 2010–2015, with a reduction of 591.98 million yuan.

The ESVs contributed by each land-use category all followed a declining trend, except for the slight recovery of ESVs contributed by forestry land and wetland (deserts are not discussed because of their extremely small area in Wuhan of less than 0.01%). ESVs of different land-use categories showed significant discrepancy. Water body accounted for the largest proportional ESV contribution (over 60%), followed by farmland (over 20%), and forestry land (over 10%), while grassland accounted for a low proportion and did not change much. Furthermore, the reduction value and rate of ESV contributed by farmland were highest and decreased by 788.65 million yuan (i.e., 29.88%), which was followed by water body, with a decrease of 778.83 million yuan. ESV contributed by grassland decreased least (by 0.25 million yuan); its decreasing rate was the second lowest and reached 27.27%.

Changes in ecosystem service values for different ecosystem services

All ecosystem services decreased during the study period (Table 3). The reduction value of hydrological regulation was highest, reaching 409.67 million yuan, which was followed by waste treatment with 398.95 million yuan. The value of raw material production decreased the least (i.e., by 51.63 million yuan). However, the declining rate of food production was highest with 26.19%, followed by soil conservation with 23.44%. Aesthetic landscape and hydrological regulation had the lowest declining rates of 13.19 and 13.71%, respectively. At each sub-stage of the study period, the values of most ecosystem services decreased relatively slowly during 1995–

Table 2 Ecosystem service values (ESVs) of each land-use category from 1990 to 2015 in Wuhan (in million yuan)

Land-use types	1990	1995	2000	2005	2010	2015
Farmland	2639.41	2559.96	2335.33	2263.95	2030.91	1850.76
Forestry land	1015.08	1001.21	1055.26	1022.47	1010.50	952.98
Grass land	9.15	8.50	7.75	7.50	7.05	6.65
Wetland	77.47	74.02	139.39	158.34	96.88	73.44
Desert	0.22	0.17	0.62	0.28	0.52	0.13
Water body	6192.94	6052.42	5827.77	5747.59	5744.19	5414.11
Total	9934.26	9696.28	9366.12	9200.12	8890.05	8298.07

2005. During 2010–2015, the values of each ecosystem service decreased rapidly, especially for hydrological regulation and waste treatment services, which decreased by 168 million yuan and 149 million yuan, respectively.

Spatial changes in ecosystem service values

Changes in overall distribution of ecosystem service values

The overall spatial distribution of ESVs in Wuhan was relatively complicated, and spatial changes showed a certain regularity (Fig. 2). Areas with extremely high and extremely low ESVs accumulated in the central region; ESVs were generally lower in the northern region, except for the region due north, where the ESVs were higher. Areas with extremely high and relatively low ESVs accumulated in the western region, and ESVs were generally higher in the southern region. Specifically, areas with high ESVs were basically consistent with the distribution of waters and were mainly found in the central and southern regions; areas with extremely low ESVs were more consistent with the distribution of construction land and were mainly found in the central region; areas with lower ESVs were basically consistent with the distribution of farmland, which spread all across Wuhan, accumulated with the water system in central and southern regions, and was more concentrated in the north. Because of the continuous

expansion of construction land, the extremely low-value areas in the central region continued to expand. During 2005–2015, the expansion of construction land had further intensified, and areas with extremely low values increased rapidly in the eastern, northern, and northeastern regions, and low-value areas kept decreasing.

Changes in the distance distribution of ecosystem service values

The interval with the highest decline of ESV changed over time (Table 4). During 1990–1995, the reduction of ESV per unit within 8 km was highest and decreased by 1455 yuan/km^2. This was followed by the 9–16-km interval with 620 yuan/km^2, while other intervals were relatively low. During 1995–2000, the highest reduction of ESV per unit was in the 9–16-km interval, where it reached 2400 yuan/km^2. From 2005 to 2010, the decreasing value of ESV per unit of the 9–16-km interval was still highest by 1816 yuan/km^2; the 17–24-km interval reached 623 yuan/km^2, while within an 8-km interval, the decreased ESV per unit decreased strongly to 425 yuan/km^2. From 2010 to 2015, the highest reduction of ESV per unit was found in the 17–24-km interval, where it declined by 1124 yuan/km^2, which was followed by 9–16 km, 25–31 km, and 33–40 km

Table 3 ESVs contributed by different services (in million yuan)

Year	Provision		Regulating				Supporting		Culture
	FP	RMP	GR	CR	HR	WT	SC	BM	AL
1990	419.24	286.30	470.74	772.72	2988.32	2575.83	696.83	978.73	745.56
1995	407.33	279.79	459.55	753.63	2919.45	2514.00	678.54	955.27	728.71
2000	377.31	272.96	447.65	739.78	2828.42	2421.41	644.72	922.36	711.50
2005	367.07	265.42	435.99	727.25	2788.11	2385.48	626.63	902.96	701.23
2010	336.97	252.34	410.13	681.51	2747.12	2326.46	579.23	866.55	689.75
2015	309.46	234.67	380.06	630.18	2578.75	2176.88	533.53	807.34	647.19

FP food production, *RMP* raw material production, *GR* gas regulation, *CR* climate regulation, *HR* hydrology regulation, *WT* waste treatment, *SC* soil conservation, *BM* biodiversity maintenance, *AL* aesthetic landscape
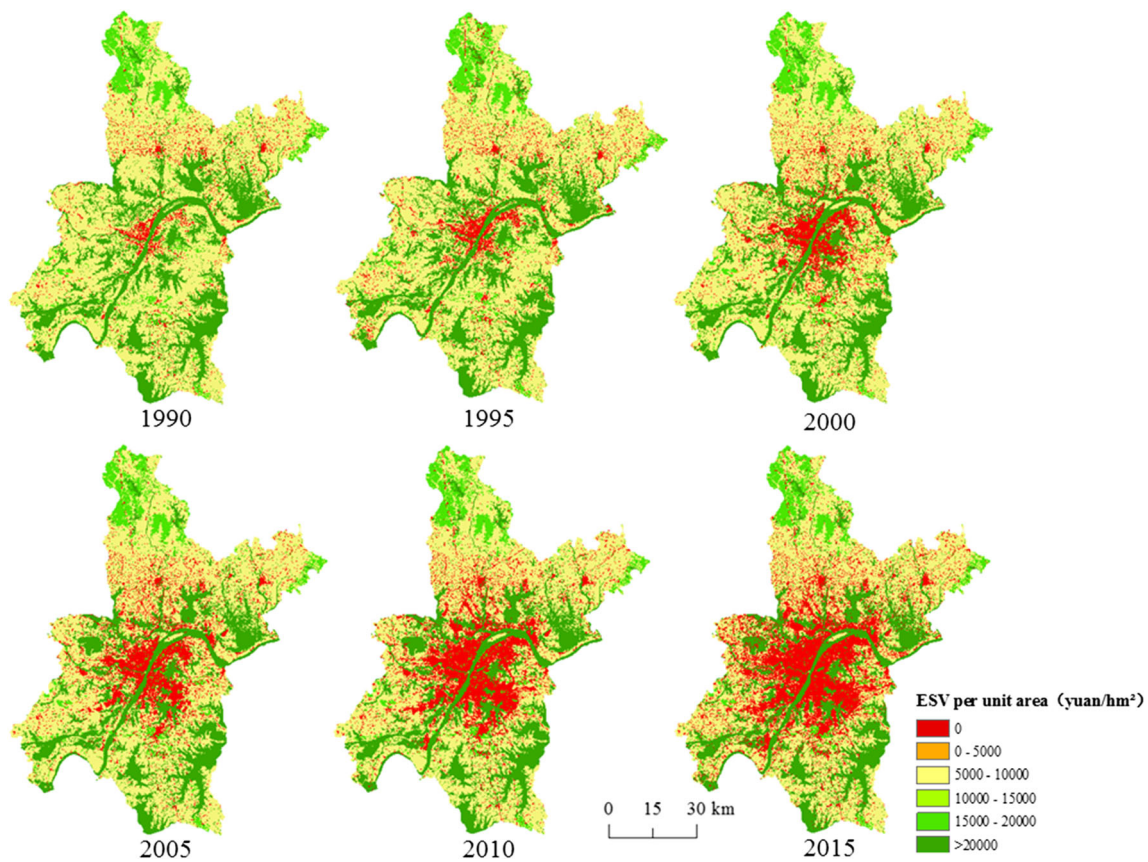
Fig. 2 Spatial distributions of ecosystem service values (ESVs) in Wuhan

intervals, which were 841 yuan/km², 908 yuan/km², and 863 yuan/km² lower, respectively.

Changes in slope distribution of ecosystem service values

The ESVs per unit in each slope interval during the study period are shown in Table 5. ESVs per unit in the 5°–9° interval were lowest in the study years except for 2015, which was followed by the 0°–4° interval. The ESVs per unit in other

intervals increased with increasing slope and reached a maximum in the 40°–44° interval. The reason was that the 5°–9° interval contained mostly farmland, and ESV contributed by farmland is low. In the 0°–4° interval, ESVs contributed by farmland and construction land were low; however, ESV contributed by water in the 0° interval compensated the total ESV in that interval. Therefore, the ESV in 0°–4° was slightly higher than that in the 5°–9° interval. The area above 10° was mainly composed of farmland and forest. With increasing

Distance (km)	Area (hm²)	1990	1995	2000	2005	2010	2015
1–8	19,988	9866	8411	7374	6059	5634	5041
9–16	59,966	13,607	12,988	10,587	10,421	8605	7764
17–24	99,639	11,918	11,627	10,962	11,172	10,549	9425
25–32	132,805	10,492	10,298	9585	9503	9249	8342
33–40	136,917	11,879	11,704	11,679	11,408	11,275	10,412
41–48	128,606	12,647	12,505	12,436	12,307	12,159	11,609
49–56	105,280	11,212	11,005	10,975	10,881	10,681	10,251
57–64	81,487	12,346	11,993	12,138	11,634	11,496	10,982
65–72	44,368	10,791	10,484	10,490	10,264	9931	9670
73–80	31,490	10,555	10,317	10,265	9665	9414	9180
81–88	8895	10,020	9734	9734	9101	8557	8322

Table 4 ESVs in different distance intervals (yuan/hm²)

Table 5 ESVs in different slope intervals (yuan/hm²)

Slope	Area (hm²)	1990	1995	2000	2005	2010	2015
0°–4°	777,005	11,525	11,243	10,809	10,645	10,272	9550
5°–9°	39,856	10,684	10,371	10,426	10,640	10,232	9678
10°–14°	17,074	14,200	13,996	14,135	13,930	13,781	13,471
15°–19°	9414	18,026	17,823	18,027	16,233	16,235	15,974
20°–24°	4148	21,833	21,634	21,757	17,932	17,798	17,558
25°–29°	1437	25,173	24,980	25,062	19,631	19,469	19,187
30°–34°	399	27,779	27,593	27,638	21,576	21,166	20,902
35°–39°	94	31,618	31,444	31,446	24,991	24,180	23,886
40°–44°	14	37,426	37,232	37,275	29,288	27,798	27,457

slope, the proportion of forest composition and habitat quality gradually increased and the ESV per unit also increased.

Changes in elevation distribution of ecosystem service values

The ESVs per unit in each elevation interval during the study period are shown in Table 6. The ESVs per unit in the 50–100-m interval were lowest in the studied years, followed by the 0–50-m interval. In other elevation intervals, the ESV per unit increased with increasing elevation and reached a maximum in the 500–800-m interval. The reason is that most of the land in the 50–100-m elevation range is farmland, with low ESV. Moreover, in the elevation range of 0–50 m, high ESVs contributed by waters compensated the low ESVs contributed by farmland and construction land. Therefore, the ESV per unit in the 0–50-m interval was slightly higher than that of the 50–100-m interval. The areas above 100 m were mainly composed of farmland and forest. With increasing slope, the ESV per unit area increased.

Urban land expansion of Wuhan

Quantitative changes of urban land expansion

Over the studied years, the quantitative analysis indicators of urban land expansion changed according to different laws (Table 7). The urban land expansion area gradually increased over time. The expansion speed was highest during 1990–1995 and first showed a trend of deceleration and then accelerated in the study periods. The expansion intensity continued to increase and was much higher during 2010–2015 than during 1990–1995; it first showed a slightly increasing trend, which was followed by a sharp increase. The damage weight of urban land expansion fluctuated and was relatively high during 1990–1995 and 2010–2015. This indicated that land with high ecological value (i.e., water bodies and forest land) accounted for a relatively large proportion of the land converted to land for urban use during 1990–1995 and 2010–2015; the ecological damage was relatively high.

Table 6 ESVs in different elevation intervals (yuan/hm²)

Elevation (m)	Area (hm²)	1990	1995	2000	2005	2010	2015
− 50–0	3	13,687	13,622	27,444	13,722	13,848	13,749
0–50	706,972	11,946	11,662	11,194	10,997	10,637	9862
50–100	106,168	8154	7878	7842	8111	7645	7320
100–150	15,467	12,851	12,634	12,778	13,620	13,235	12,956
150–200	7178	15,364	15,174	15,263	15,408	15,289	15,045
200–250	4453	18,162	17,974	18,033	16,639	16,754	16,486
250–300	2891	21,662	21,422	21,537	17,895	17,994	17,722
300–350	2114	24,708	24,473	24,565	18,704	18,837	18,575
350–400	1544	26,699	26,508	26,569	19,583	19,496	19,214
400–450	953	28,448	28,241	28,315	19,774	19,504	19,218
450–500	710	29,150	28,968	28,988	17,670	17,602	17,351
500–800	989	29,443	29,262	29,328	16,401	16,401	16,195

Table 7 Urban land expansion changes

Year	Area (hm^2)	Speed	Intensity	Damage weight	Slope (%)	Elevation (m)	Distance (km)
1990–1995	19,730.83	50.93	2.32	15.95	2.11	35.52	20.74
1995–2000	22,074.41	37.75	2.60	12.17	1.76	25.69	22.39
2000–2005	25,365.98	31.49	2.99	14.19	1.92	30.50	24.30
2005–2010	38,673.56	36.52	4.55	11.95	1.90	31.20	24.14
2010–2015	53,179.67	36.78	6.26	16.53	1.78	30.40	32.55

Spatial changes of urban land expansion

The spatial changes of urban land expansion in Wuhan are shown in Table 7. From 1990 to 1995, the expansion distance was closest to the center of Wuhan. With time, the urban expansion slowly continued, and from 2010 to 2015, the expansion distance increased to 32.5 km, which was much further than in the previous 20 years. The change of expansion elevation followed a trend of "decreased first and then increased" with a large variation from 1990 to 2000. Over the next 10 years, the expansion elevation remained relatively stable at around 30 m. The overall terrain of Wuhan is flat, and the expansion slope of urban land changed little. The largest expansion slope was during 1990–1995 (by 2.11%), and the smallest was during 1995–2000.

Spatial correlation between ecosystem service values and urban land expansion

Global autocorrelation

In the studied years, Moran's I of each ecosystem service was less than 0 and passed the significance test. This suggests that a significant negative correlation exists between urban spatialization and ecosystem services (Table 8). A strong negative correlation was found between food production service

and urban spatialization, with the highest value of − 0.352, indicating that urban land expansion had the most negative impacts on food production service. This could be attributed to the major change of farmland to urban land, which caused a continuous decline of food supply capacity. The services of soil conservation, climate regulation, raw material production, gas regulation, and biodiversity maintenance had relatively strong negative correlation with urban spatialization. Moran's I of waste treatment and aesthetic landscape were relatively low, with maximal values of − 0.075 and − 0.073, respectively, indicating that urban land expansion had relatively little impacts on these ecosystem services. The Moran's I of hydrological regulation service was lowest, indicating that urban land expansion had minimal impact on hydrological regulation.

Local autocorrelation

The local spatial autocorrelation LISA cluster maps are shown in Fig. 3. The spatial clustering relationship between the total ESV and urban land use area changed greatly over time. Before 2000, the HL and LL cluster areas were mainly distributed in the northern region; the HL cluster area decreased, while the LL cluster area increased during the study period. Since 2000, the HL cluster area in the central region increased gradually. In the western region, small number of HL and LL

Table 8 Bivariate Moran's I between urban spatialization and ecosystem services

Year	Provision		Regulating				Supporting		Culture	Total
	FP	RMP	GR	CR	HR	WT	SC	BM	AL	
1990	− 0.036*	− 0.142**	− 0.145**	− 0.158**	− 0.07**	− 0.062**	− 0.130**	− 0.169**	− 0.094**	− 0.118**
1995	− 0.102**	− 0.158**	− 0.172**	− 0.175**	− 0.029*	− 0.024*	− 0.185**	− 0.169**	− 0.057*	− 0.094**
2000	− 0.352**	− 0.194**	− 0.222**	− 0.200**	− 0.040*	− 0.043*	− 0.296**	− 0.224**	− 0.065**	− 0.127**
2005	− 0.151**	− 0.219**	− 0.231**	− 0.128**	− 0.046*	− 0.051**	− 0.222**	− 0.225**	− 0.073**	− 0.141**
2010	− 0.207**	− 0.253**	− 0.270**	− 0.268**	− 0.063**	− 0.075**	− 0.274**	− 0.266**	− 0.090**	− 0.179**
2015	− 0.169**	− 0.288**	− 0.290**	− 0.270**	− 0.047*	− 0.058**	− 0.255**	− 0.259**	− 0.089**	− 0.175**

** and * indicate that the correlation is significant at confidence levels of 99 and 95%, respectively

FP food production, *RMP* raw material production, *GR* gas regulation, *CR* climate regulation, *HR* hydrology regulation, *WT* waste treatment, *SC* soil conservation, *BM* biodiversity maintenance, *AL* aesthetic landscape
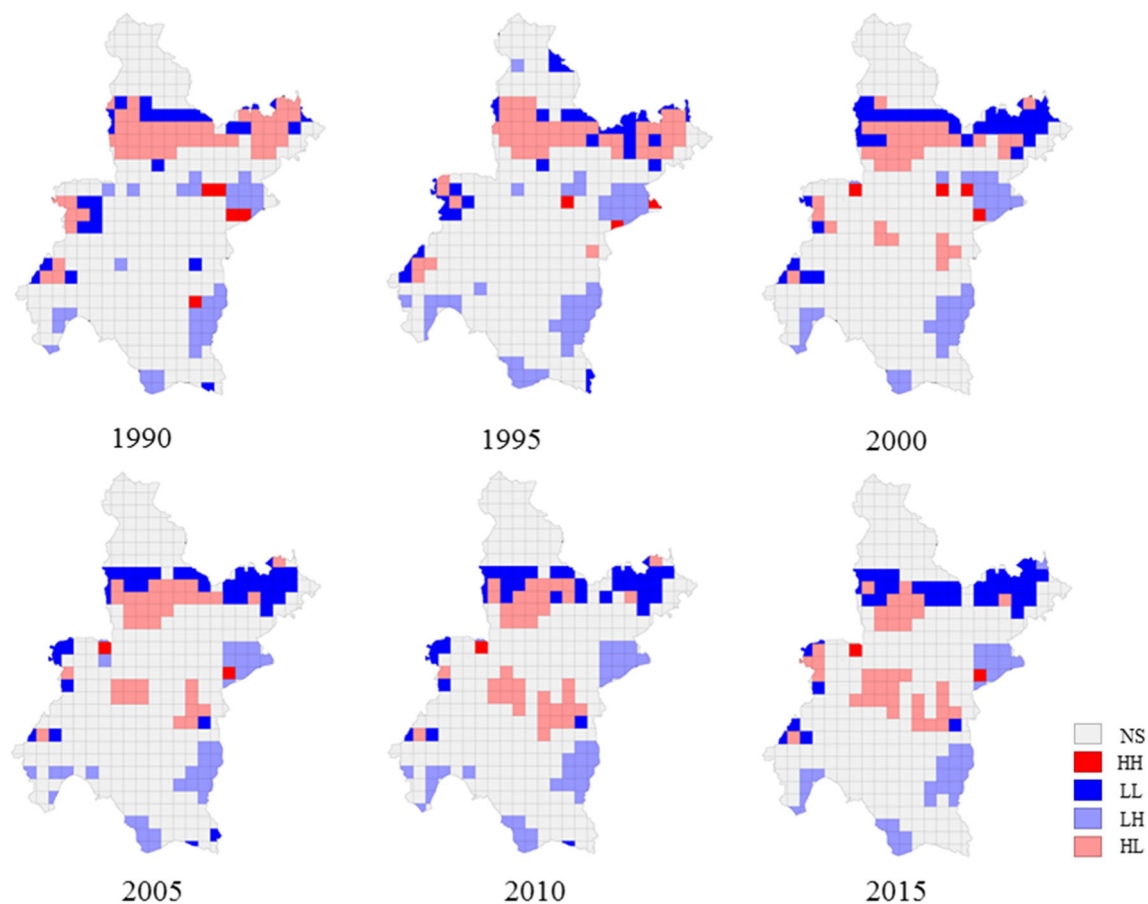
Fig. 3 LISA cluster maps between total ESVs and urban spatialization

cluster areas were staggered distributed. LH cluster areas were mainly distributed in the southern and eastern regions.

Impacts of urban land expansion on ecosystem services

Factors of urban land expansion include expanding area, slope weight, elevation weight, distance weight, and expansion damage weight (Table 9). The reduction of the total ESV was affected by the urban expansion area, expansion elevation, expansion distance, and expansion damage weight. Among these, the total ESV reduction was negatively affected by the expansion area and expansion damage weight, while elevation and distance positively impacted the total ESV. Through the standardization coefficient, the influence degree of each factor above on the reduction of total ESV was ranked as followed: expansion area > expansion distance > expansion damage weight > expansion elevation.

The influencing factors of urban land expansion on the services of gas regulation, climate regulation, and biodiversity maintenance were identical to those of the total ESV reduction. Specifically, the impact degree of each factor on biodiversity maintenance was similar to that on the total

ESV reduction, while gas regulation and climate regulation were mainly affected by the expansion area. Both food production and soil conservation were negatively affected by the expansion area, slope, and expansion damage weight, among which, the influencing degrees of the expansion area and the expansion damage weight were higher than that of the expansion slope. Hydrological regulation, aesthetic landscape, and waste treatment functions were negatively affected by the expansion area, elevation weight, and expansion damage weight. In particular, raw material production was only negatively affected by the expansion area.

Discussion

Impacts of urban land expansion on spatial and temporal distributions of ecosystem service values

The expansion of urban land is inevitable during the process of urban development. The encroachment of urban construction land on other types of land use will destroy the stability of the original ecosystems, thus also affecting ecosystem

Table 9 Response coefficients of ecosystem services to urban land expansion

Ecosystem services		Distance		Slope		Elevation		Damage weight		Area	
		N-SD	SD	N-SD	SD	N-SD	SD	N-SD	SD	N-SD	SD
Provision	FP			89418433**	0.283			42185798**	0.754	633**	0.686
	RMP									328**	0.997
Regulating	GR	− 635,392**	− 0.665			− 1,072,743*	− 0.250	25204302*	0.413	937**	1.332
	CR	− 264,705**	− 0.344			− 537,783*	− 0.169	18378773*	0.333	2876**	1.982
	HR					− 20,546,228*	− 0.784	22010865*	0.860	3762*	0.875
	WT					− 58,501,957**	− 2.682	92794888**	2.953	17285**	4.833
Supporting	SC			137162637**	0.332			53810029**	0.557	684**	0.567
	BM	− 3,125,142**	− 1.868			− 10,407,750**	− 1.385	63255131**	1.530	3291**	2.67
Culture	AL					− 3,984,759*	− 0.618	19864899**	0.825	888**	0.840
Total ESV		− 52,698,634**	− 3.009			− 182,133,572**	− 2.314	88351543**	2.516	51573**	3.997

FP food production, *RMP* raw material production, *GR* gas regulation, *CR* climate regulation, *HR* hydrology regulation, *WT* waste treatment, *SC* soil conservation, *BM* biodiversity maintenance, *AL* aesthetic landscape, *N-SD* non standardization, *SD* standardization

*Coefficient is significant at the level of 0.05

**Coefficient is significant at the level of 0.01

services. Previous studies have indicated that urban expansion causes a degradation of ecosystem services. For instance, Lin et al. (2013) have shown that the urban space expansion requires a large area of eco-land, resulting in the reduction of ESVs; Wang et al. (2019) found that both food production and regulation services decreased dramatically in response to urban land expansion; Huang et al. (2019) found that urban expansion would exert negative impacts on the wetland landscape pattern and ecosystem services. The results of the present study show that the total ESV of Wuhan decreased by 1638.19 million yuan from 1990 to 2015 and all ecosystem services decreased simultaneously. Significantly, during 2010–2015, the urban expansion activity intensified, the urban land expansion area, intensity, and damage weight reached the highest, caused a sharp decline in the total ESV. These results indicated that the large-scale, high-intensity, and rapid expansion of urban land exacerbated the degradation of ecosystem services, which is consistent with the results of previous studies.

In addition, the variation of the spatial distribution of ESVs was further explored. Large areas of eco-land with extremely high ESV were encroached by the widespread urban construction land, resulted in the areas with extremely low ESV increased rapidly and sprawled widely from the urban center (Fig. 2). The areas with the highest ESV reduction moved from the interval within 8 km to the 17–24-km interval because of the continuous shifting of the gravity of urban land expansion over time. Land available for the conversion of the urban construction land reduced within the areas which close to the urban center, urban land expansion gradually weakened, and the pressure on the ecosystem services was relieved. Consequently, the ESV reduction within the 8-km interval

decreased significantly after 2005. However, in order to meet the land demand of urban development, urban land expansion spread to the urban periphery regions, which resulted in the ESV reduction within the 41–46-km interval (which is far from the urban center) increased significantly. Moreover, the slope and elevation distribution changes of ESVs indicated that the ESVs above 15° slope and 200 m elevation decreased obviously during 2000–2005. These regions were mainly composed of forest and consequently, one possible reason may be that urban land expansion caused serious destruction on forestry ecosystems, and thus, their ESV decreased greatly.

Qualitative and quantitative relationship between urban land expansion and ecosystem service values

Spatial autocorrelation analysis was used to analyze the qualitative relationship between ecosystem services and urban land expansion in Wuhan. A negative correlation was found between urban spatialization and each ecosystem service (Table 8), suggesting that urban land expansion caused a decline of ecosystem services. Zhang et al. (2018) also found the negative spatial correlations between all ecosystem services and urbanization in Wuhan. However, the absolute values of Moran's *I* were relatively smaller than that of the previous study. The reasons are as follows: Primarily, the area of the urban land in each spatial unit was took as the index of the urban spatialization in this study. Differently, Zhang et al. (2018) measured the urbanization index in the dimensions of population growth, economic development, and urban land expansion to explore the relationship between urbanization and ecosystem services. Besides, the calculation of ESVs was based on Xie et al. (2008), while Zhang et al. (2018)

quantified each individual ecosystem service using different methods according to the previous studies. The absolute value of Moran's *I* between urban spatialization and food production service was highest, indicating that urban land expansion had the greatest impact on food production, and explains the prominent decline of food production services. Which is because farmland is the main land category encroached upon by the urban land expansion in Wuhan during the study period, large-scale loss of farmland resulted in the serious decline of food supply service. The same situation also happened in Nanjing and Beijing–Tianjin–Hebei regions of China; the expansion of urban land take place at the expense of farmland caused the food supply service decreased dramatically (Wang et al. 2019; Yuan et al. 2018). Moreover, the absolute value of Moran's *I* between urban spatialization and hydrology regulation was smallest; however, the calculated decrease of ESV contributed by hydrology regulation service was largest. This is the result of the greatest proportion of ESV contributed by hydrology regulation in the total ESV, and even the slight impact of urban land expansion will cause a prominent decrease ESV of hydrology regulation. The variation of different cluster areas (Fig. 3) illustrates that the HL cluster areas in the northern region gradually decreased while the LL cluster area increased. This can be largely attributed to the gradual weakening of urban land expansion in the northern region. Since 2000, the HH cluster areas in the central region increased, mainly because urban land had spread to the periphery from the urban center; LL cluster areas are mostly distributed in the southern and eastern regions, as these regions are far from the urban center and less affected by the urban land expansion. Moreover, water bodies were distributed in these regions; hence, the ESVs per unit area were relatively high. Similarly, Ouyang et al. (2019) concluded that the HL cluster areas were concentrated in the urbanized regions, while the LH cluster areas were distributed in the regions with low urbanization level in the Changsha–Zhuzhou–Xiangtan urban agglomeration.

Through the linear regression, the quantitative relationship between urban land expansion and ecosystem services was explored. Results show that urban land expansion area is significantly correlated with all ecosystem services, expansion damage weight is significantly correlated with all services except for the raw material production service. With a 1-hm^2 and 1-unit increase of urban land expansion, the total ESV decreased 51,573 yuan, and 88,351,543 yuan, respectively. Standardization coefficients indicate that urban expansion area and damage weight both had the greatest impact on waste treatment service and the next was the biodiversity maintenance service. The main reason is that waste treatment and biodiversity maintenance services were mainly provided by water body and wetland, and the unit urban land expansion area and damage weight had greater impacts on the areas with high ESVs. The impacts of urban land expansion area and

damage weight on food supply service were not prominent; however, the encroachment of large areas of farmland by urban land expansion also caused a sharp decline of food production service. The elevation and distance of urban land expansion have positive effects on ESVs. This is because the areas with high ESVs in Wuhan are mainly distributed in areas with low elevation and the south–central region, while the urban expansion was mainly concentrated in the central and middle northern regions. Thus, the reduced ESV decreased with increasing elevation and distance of urban expansion. The expansion slope had the smallest impacts on ecosystem services and only affected food production and soil conservation. This can be largely attributed to the fact that areas that provide food production and soil maintenance services (such as farmland and forestry land) were mainly distributed in medium and high slope regions. Therefore, the decreased ESV contributed by both services increased with increasing expansion slope.

Limitations and further work

The calculation of ESV in this paper is based on the ESV evaluation model proposed by Costanza et al. (1997) and the equivalent value per unit area of ecosystem services in China reported by Xie et al. (2008). Moreover, the present study applied corrections on the ESV to accurately reflect the spatial and temporal changes of ESVs. However, only NPP was used for ESV correction in each spatial unit; however, the NPP value of water body is 0, which made the spatial correction of ESV incomplete. The time value of currency was used for temporal correction, but inflation can be reflected by multiple indicators, and many methods are available for spatial correction. The most applicable correction scheme needs to be further identified. In addition, in the calculation process, all ecosystem services were regarded as equally important, which hardly reflects the dynamic changes and spatial agglomeration of ecosystem services (Li et al. 2011; Wu et al. 2017). To this end, further research could explore the optimum correction method of ESV and consider the relative importance and spatial richness of various ecosystem services.

The impacts of urban land expansion on ecosystem services are complex (Liu et al. 2020). The present paper presents a thorough inquiry into the impacts of the spatial and temporal changes of urban land expansion on ecosystem services in Wuhan. In practical terms, the impacts of urban land expansion on ecosystem services combined both direct and indirect impacts. Direct impacts are caused by the encroachment of urban land expansion, while indirect impacts are caused by the conversion between other land types as a result of urban land expansion. The indirect impacts need to be further analyzed. Moreover, the results showed that the changes in slope and elevation distribution of ESVs were almost identical; therefore, spatial distribution of ESV analysis could search

for the close relationship between the slope and elevation distribution and combine these two aspects.

Conclusion and policy implications

Using Wuhan as case study, this study estimated the variations of ESV and urban land expansion and explored both the spatial and temporal impact characteristics on ecosystem services of urban land expansion through spatial autocorrelation and linear regression. The results showed the following:

1. The intensification of urban land expansion (measured by ESVs) continuously decreased from 1990 to 2015, and the ESV contributed by farmland declined the most among all land-use categories.
2. Areas with extremely low ESVs spread widely outward from the urban center, corresponding to the direction of urban land expansion of Wuhan.
3. There is a significant negative correlation between urban land expansion and each ecosystem service. Food production was affected the most because of the large encroachment of urban land on farmland in Wuhan.
4. The area of urban land expansion is the main reason for the decline of ESVs, as this affected all ecosystem services, while the expansion slope only slightly affected food production and soil conservation.

To balance the relationship between urban development and ecosystem sustainability, a number of strategic suggestions should be implemented for the future urban land expansion of Wuhan. Firstly, the government should control the scope of the central urban area, as the ESVs per unit are relatively low in regions 65 km away from the urban center. The government may consider to build satellite cities in the regions further away from the center. Secondly, the stock construction land should be utilized properly, reasonable planning should be promoted, and the area of new construction land should be reduced. Ultimately, the occupation of land-use categories with high ESV (i.e., water body, forestry land, and wetland) by urban land expansion should be reduced to control the decline of the total ESV.

Declarations

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