Research on the spatiotemporal changes and driving factors of ecosystem service value in the urban agglomeration of the middle and lower reaches of the Yangtze River

Xingnan Tian *

School of Public Administration Mpa Education Center, Shanxi University Of Finance And Economics, Taiyuan, China, 030031

* Corresponding Author Email: 13835646737@139.com

Abstract. Land use change is a threat to the sustainable development of economic society and ecological environment due to the intensification of human activities. Taking the urban agglomerations in the middle and lower reaches of the Yangtze River as the research object, this paper innovatively integrates the socio-economic and land use data from 2010 to 2020, uses the equivalent factor method to evaluate the ecosystem service value (ESV), constructs the socio-economic pressure index (SEPI), and discusses the relationship between the two with the help of geographical detectors. The study found that: ① compared with 2010, the area of cultivated land and unused land decreased in 2020, while the area of other land types increased; ② ESV showed a "rise decline rise" fluctuation trend, which was significantly driven by water resources supply and hydrological regulation function; ③Ecological factors are the main driving force affecting the spatial differentiation of ESV, while economic factors affect the ecological environment indirectly. The study reveals the key path of regional land use optimization from the perspective of socio-economic and ecological synergy, and provides a scientific basis for sustainable development.

Keywords: Urban Agglomeration in the Middle and Lower Reaches of the Yangtze River, Ecosystem Service Value, Geo Detector.

1. Introduction

Land use change is closely related to the value of ecosystem services [1]. It not only reshapes the land pattern and efficiency, but also deeply relates to the diverse service functions of the ecosystem, which is the core driving force for value change. Ecosystem services [2-8] encompass the material and non-material benefits that humans directly or indirectly obtain from ecosystems, and the value of ecosystem services is the monetary quantification of these service functions. Its spatiotemporal evolution maps the external appearance and internal operational mechanisms of ecology.

As early as the 1960s, foreign countries have been involved in the study of ecosystem service value. The initial exploration of Yellowstone National Park by the United States opened the door to research. In the 1990s, Costanza et al.'s global quantitative assessment sparked a global trend, and Germany's precise measurement of the carbon sink service value of black forests provided key guidance for forest management. Although it started late in China, it actively draws on and combines local characteristics to deeply explore. For example, the tropical rainforest in Xishuangbanna, Yunnan promotes regional ecological and economic coordination in biodiversity and cultural tourism service value research, and the urban green space and farmland service value research in the Beijing Tianjin Hebei region helps with urban agglomeration ecological planning. Nowadays, research at home and abroad is mutually reinforcing and jointly moving towards deeper fields [9-12].

The urban agglomeration in the middle and lower reaches of the Yangtze River used to be a model of coordinated development between ecology and economy. The ecosystem was like a magnificent painting, with wetlands, water systems, forests, and farmland interwoven in a staggered manner. The natural landscape was rich and charming, and human activities were also quite active. Urban expansion, industrial prosperity, and large population inflows. But now, rapid development has caused many difficulties. On the one hand, ecological spaces have been severely damaged, wetlands have been extensively developed, lake areas have sharply decreased, urban waterlogging occurs frequently during flood seasons, a large amount of property has been damaged, and residents' lives have been disrupted; industrial and agricultural pollution is rampant, soil quality is deteriorating, crop yields are decreasing, water bodies are murky, fisheries are almost collapsing, smog covers the sky, and respiratory diseases are high. On the other hand, the problem of imbalanced value of ecosystem services is prominent, with ecological land being swallowed up by urban expansion, ecological regulation functions weakening, and urban heat island effect intensifying, industrial layout chaotic, and traffic congestion costs soaring. All of these are due to poor ecosystem planning, which cannot help promote orderly economic development, resulting in imbalanced value of services such as supporting the economy and reducing costs. It is urgent to reverse the predicament.

This study focuses on the urban agglomeration in the middle and lower reaches of the Yangtze River, deeply exploring the synergistic relationship between ecosystem service value (ESV) and socio-economic factors, and filling the existing gap. Collect diverse data such as satellite remote sensing images, geographic information, and socio-economic statistics through multiple channels to comprehensively analyze land use evolution. Different from the previous approach of understanding driving factors from a natural ecological perspective, this article innovatively analyzes the ESV driving mechanism from a socio-economic perspective, uses the equivalent factor method to analyze the spatiotemporal characteristics of ESV, uses Pearson correlation coefficient to identify key driving factors, and constructs the Social Economic Pressure Index (SEPI) to input into a geographic detector. Based on this, land optimization planning, regulatory system improvement, and regional coordinated development strategies are formulated to promote the benign interaction between regional ecology and economy, laying a foundation for ecological protection and sustainable development of urban agglomerations.

2. Research areas and data sources

2.1. Research Area

The Yangtze River Delta urban agglomeration in the middle and lower reaches of the Yangtze River is located near the mouth of the Yangtze River on the eastern coast of China. Its geographical coordinates range from 30 ° 34 ′ to 32 ° 34 ′ N and 118 ° 20 ′ to 123 ° 25 ′ E, forming an irregular triangle with an area of approximately 211700 square kilometers. The land use is mainly construction land, arable land, and water bodies, making it an economically developed and highly urbanized region with significant transportation and industrial advantages. However, in the process of development, there are ecological problems such as land use change, water pollution, and air pollution. Urbanization encroaches on natural land, destroys biological habitats and ecological regulation functions, and water pollution affects water resource utilization, aquatic ecosystems, and productivity. This study focuses on 26 representative cities with diverse ecological protection, economic models, and geographical environments, including Anqing, Changzhou, and Chizhou, to explore the spatial differentiation of urban ecosystem service values in the Yangtze River Delta region and provide empirical basis for analyzing their internal mechanisms and influencing factors. But this does not mean that the research on the Yangtze River middle and lower reaches urban agglomeration is limited to this. In fact, the scope of the Yangtze River middle and lower reaches urban agglomeration is broader, including more cities, and each city has its unique ecosystem service value, which is crucial for the sustainable development of the entire urban agglomeration.

2.2. Data sources

The selected indicators are of great significance in exploring the coordinated development of regional ecology and economy. In terms of land resources, arable land ensures food supply, forest land maintains stable ecological balance, water bodies conserve water sources and resist disasters, grasslands maintain biodiversity, construction land is closely related to urbanization rate, and its expansion speed reflects the urbanization process. If the planning is not good, a large amount of ecological land will be occupied, which will break the ecological balance. Unused land has both advantages and disadvantages; at the level of economic development, GDP and per capita GDP determine the scale of ecological investment, and the proportion of the secondary industry affects the distribution of labor force and pollution level; in the field of energy resources, water resources and electricity consumption are related to aquatic ecology, and unreasonable use will lead to a series of problems. These indicators are intertwined and profoundly affect the regional ecological and economic situation.

The land use data in this study was taken from the annual land cover product dataset of Wuhan University, with a resolution of 30m. According to its classification system, it is divided into six categories: cultivated land, forest land, grassland, water area, unused land, and construction land; socio economic data is mainly sourced from statistical yearbooks of various cities, GDP data is sourced from the Resource and Environmental Science and Data Platform, and precipitation data is sourced from the National Earth System Science Data Center. The data classification is shown in Table 1.

Table 1. Data Classification and Indicators.

data classification	index	Company
Socio economic data	Gross Domestic Product (GDP)	RMB100mn
	Per capita GDP	Ten thousand yuan
	Labor input	ten thousand people
	Water resource usage	Billion cubic meters
	Electricity consumption	Billion kilowatt hours
	Environmental greening area	hectare
	Proportion of secondary industry	%
	Urbanization rate	%
	grain yield	Ten thousand tons
	precipitation	millimeter
Land use data	Cultivated land	Ten thousand acres
	woodland	Ten thousand acres
	grassland	Ten thousand acres
	land used for building	Ten thousand acres
	waters	Ten thousand acres
	Unutilized land	Ten thousand acres

2.3. Research Methods

2.3.1. Equivalent Factor Method

Xie Gaodi et al. constructed an ecosystem service value assessment system that is in line with the actual situation in China based on the equivalent factor method proposed by Costanza et al [13]. This study calculates the ecosystem service value of the urban agglomeration in the middle and lower reaches of the Yangtze River based on the specific situation and the results of Xie Gaodi et al., mainly covering the following three parts.

1) Determine the equivalent value table of ecosystem services for the urban agglomeration in the middle and lower reaches of the Yangtze River. Referring to the ecosystem service value equivalent table established by Xie Gaodi et al., combined with the specific situation of the Yangtze River middle and lower reaches urban agglomeration, the unit area ecosystem service value equivalent of the Yangtze River middle and lower reaches urban agglomeration is obtained (Table 2).

Table 2. Equivalent Value of Ecosystem Services per Unit Area in the Urban Agglomeration of the Middle and Lower Reaches of the Yangtze River

First level service	Secondary service	Cultivated land	woodland	grassland	waters	Unutilized land	land used for building
Supply services	Food production	1.36	0.29	0.38	0.80	0.00	0.00
	production of material	0.09	0.66	0.56	0.23	0.00	0.00

Adjustment service	Water resource supply	-2.63	0.34	0.31	8.29	0.00	0.00
	Gas regulation	1.11	2.17	1.97	0.77	0.02	0.00
	Climate regulation	0.57	6.50	5.21	2.29	0.00	0.00
	clean the situation	0.17	1.93	1.72	5.55	0.10	0.00
	Hydrological regulation	2.72	4.74	3.82	102.24	0.03	0.00
Support services	Soil conservation	0.01	2.65	2.40	0.93	0.02	0.00
	Maintain nutrient cycling	0.19	0.20	0.18	0.08	0.00	0.00
	bio-diversity	0.21	2.41	2.18	2.55	0.02	0.00
Cultural services	Aesthetic Landscape	0.09	1.06	0.96	1.89	0.01	0.00

2) In order to avoid the impact of changes in grain prices in different years on the equivalent value of ecosystem services per unit area in the middle and lower reaches of the Yangtze River urban agglomeration, referring to the research results of Lou Peiqing et al. and Zhou Su et al., it was divided into six periods to calculate the average yield and price of various food crops in the middle and lower reaches of the Yangtze River urban agglomeration from 2010 to 2020. The formula is as follows:

$$E_a = \frac{1}{7}\sum_{i=1}^{n}\frac{m_i p_i q_i}{M}(f = 1,2,\dots,n) \tag{1}$$

Among them, Ea represents the economic value of providing crop production services per unit area of farmland ecosystem (yuan/hectare); this study represents the i-th crop, and this study selected three types of main crops in the urban agglomeration of the middle and lower reaches of the Yangtze River, namely wheat, corn, and rice, for calculation; M_i is the planting area of the i-th crop (in hectares); P_i is the national average price of the i-th crop in the corresponding year (yuan/ton); Q_i is the yield per unit area of the i-th crop (tons/hectare); M is the total planting area (in hectares) of the three main crops.

3) The method for calculating the ecosystem service value of the urban agglomeration in the middle and lower reaches of the Yangtze River is as follows:

$$ESV = \sum_{i=1}^{n}(A_i \times V_i) \tag{2}$$

In the formula: ESV is the ecosystem service value (yuan); this study is the type of land use; N is the number of land use types in the study area; A_iThe area (hm2) of i types of land use; V_iEquivalent coefficient of ecosystem service value (yuan · hm-2) corresponding to i types of land use.

2.3.2. Pearson correlation coefficient

Pearson correlation coefficient method is an effective method for measuring the degree of linear correlation between variables, which is used to preliminarily screen data indicators. It conducts analysis based on variable observation data, first determining the mean of each variable, and then calculating the correlation coefficient according to a specific formula, as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{3}$$

(Where $x,\ y$ is the variable observation sequence,$\overline{x}\ \ \overline{y}$is the mean, and is the data volume). The coefficient values $[-1,1]$ are close to 1 indicating strong positive correlation, close to -1 indicating strong negative correlation, and close to 0 indicating no linear correlation.

2.3.3. Socio Economic Stress Index (SEPI)

The Socio Economic Stress Index (SEPI) is a comprehensive indicator that quantifies the potential pressure of socio-economic activities on ecosystems, and is suitable for revealing the contradictory relationship between socio-economic development and ecosystem service value (ESV). The construction method is as follows: ① Select indicators and construct the SEPI indicator system; ② Calculate weights based on entropy weight method; 3. Calculate SEPI. The formula is calculated as follows:

For positive indicators,

$$X'_{ij} = \frac{X_{ij} - min(X_{ij})}{max(X_{ij}) - min(X_{ij})} \tag{4}$$

For negative indicators,

$$X'_{ij} = \frac{max(X_{ij}) - X_{ij}}{max(X_{ij}) - min(X_{ij})} \tag{5}$$

Calculate the entropy value of the i-th indicator,

$$S_i = \frac{-(\sum M_i \times ln\, M_i)}{ln\, n}, M_i = X'_{ij} / \sum X'_{ij} \tag{6}$$

In the formula, Si represents the entropy value, Mi represents the proportion of the i-th sample, and n is the number of evaluation samples. Calculate the weight of indicators.

$$W_i = (1 - S_i) / \sum(1 - S_i) \tag{7}$$

Finally, calculate the comprehensive score of SEPI.

$$\mathrm{U_i} = \sum \mathrm{W_i} \times \mathrm{X'_{ij}} \tag{8}$$

2.3.4. Geographic Detector

Geographic detector is an important tool for analyzing spatial heterogeneity and its driving factors. This article combines the spatial overlay analysis of SEPI and ESV to further deepen the spatial visualization and interpretation of the results, revealing the hotspot distribution of regional ecological pressure. The main calculation formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h {\sigma_h}^2}{N\sigma^2} \tag{9}$$

In the formula, q represents the explanatory power of factor (X) on a certain ESV (Y), and the larger the value, the greater the influence of the independent variable (X) on the dependent variable (Y); The N_h number σ_h of units representing type h and the variance representing type h.

3. Results Analysis

3.1. Land Use Analysis of Urban Agglomeration in the Middle and Lower Reaches of the Yangtze River

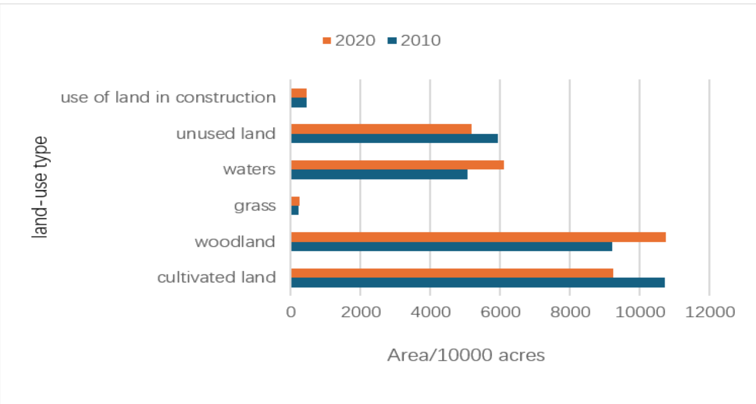

Figure 1. Land use changes in the urban agglomeration of the middle and lower reaches of the Yangtze River over the past 10 years.

As shown in Figure 1, the urban agglomeration in the middle and lower reaches of the Yangtze River has undergone profound changes in land use patterns from 2010 to 2020. This area is interwoven with river networks and dotted with lakes. Under the strategic guidance of "jointly protecting and not developing", various regions are actively taking action. On the one hand, the vigorous promotion of wetland restoration projects has significantly increased the water area, adding 1061.86 hectares, an increase of 21.0%, greatly improving the efficiency of water conservation and ecological regulation, and expanding the habitat space for numerous aquatic organisms; At the same time, with the advantage of abundant precipitation, afforestation activities have been vigorously carried out, and the forest area has increased by 1552.22 hectares, an increase of 16.9%, like a green barrier stabilizing the ecological foundation. The grassland also saw a slight increase, with an increase of 15.74 hectares or 6.9%. On the other hand, due to the implementation of the ecological restoration policy and the demand for urban expansion, the cultivated land has decreased by 1487.04 hectares, a decrease of 13.9%, and the prudent development of unused land has decreased by 755.59 hectares, a decrease of 12.8%. However, the increase in construction land is relatively small, and overall it is steadily moving towards a balance between ecology and development coordination.

3.2. Analysis of changes in ecosystem service value of urban agglomerations in the middle and lower reaches of the Yangtze River

3.2.1. Time Evolution

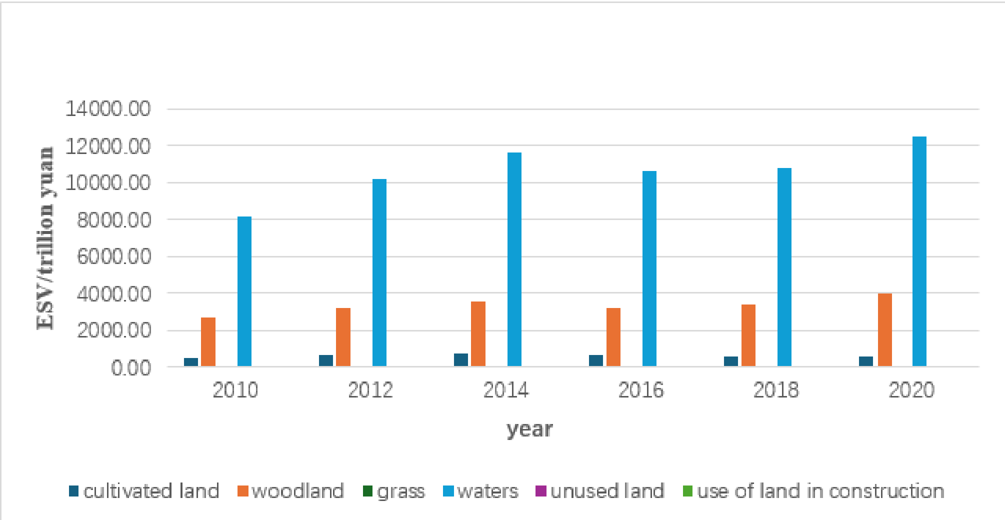

Figure 2. ESV Status of Various Land Types in the 6th Phase of the Yangtze River Midstream and Downstream Urban Agglomeration.

Through the interpretation of Figure 2, the total ESV value of the Yangtze River middle and lower reaches urban agglomeration showed a trend of "first increasing, then decreasing, and then increasing" from 2010 to 2020, with significant changes in land use and ESV. There are numerous rivers and lakes in the area. With superior natural conditions, under the policy of "joint protection", wetland restoration and afforestation are actively carried out, and the area of wetlands and forests has increased significantly, strengthening the ecological barrier. From 2010 to 2014, water bodies relied on strong hydrological regulation and water supply to become the main force of ESV, accounting for over 40%. Forests, cultivated land, and grasslands each played their respective roles, resulting in a total ESV value increase of about 15% in four years. However, from 2014 to 2016, local pollution and excessive development caused ecological imbalance, resulting in a sharp drop of nearly 10% in ESV. During the period from 2016 to 2020, with timely corrections from the local government and the public, we vigorously restored the ecology, prudently developed unused land, planned construction land reasonably, guided water bodies, coordinated forest land, etc. As a result, ESV rebounded by over 8%, and the ecological economy returned to the right track towards a win-win situation.

3.2.2. Spatial Evolution

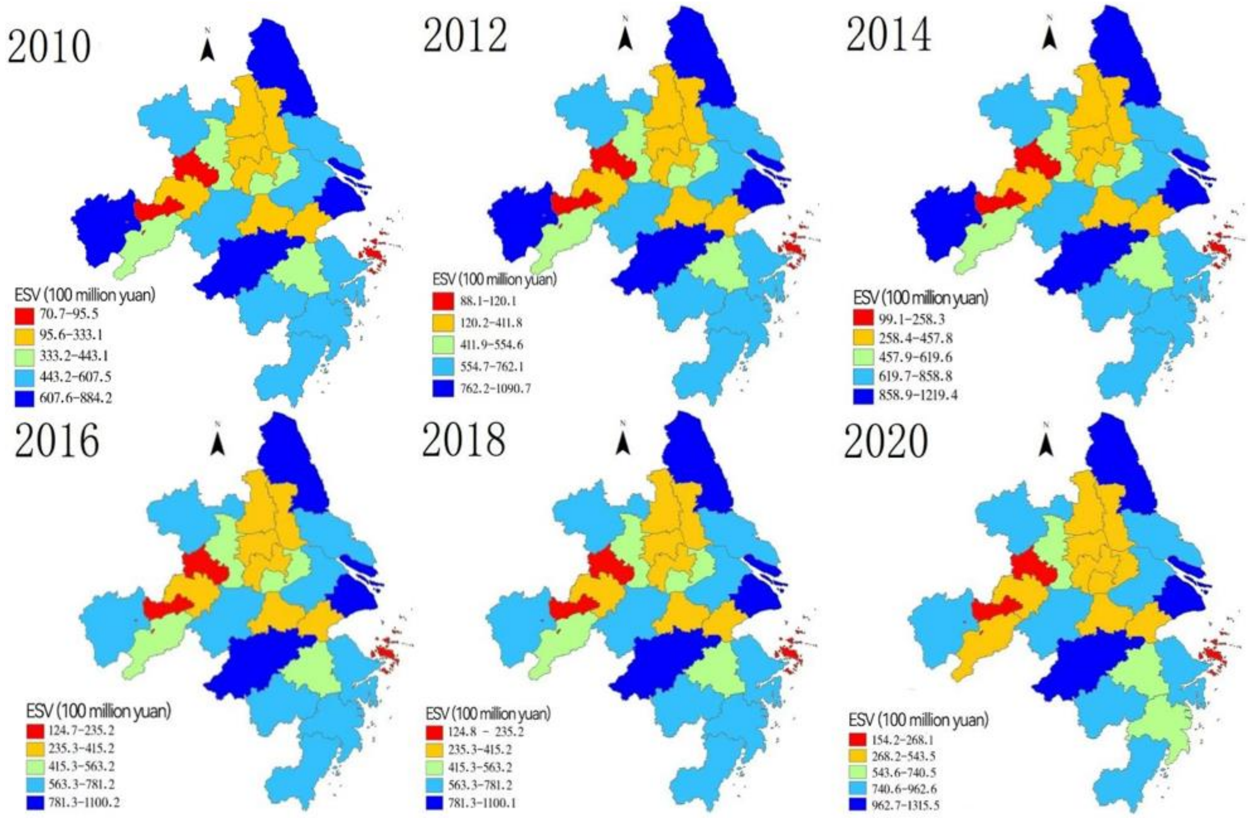

Figure 3. Changes in ESV of Cities in the 6th Phase of the Yangtze River Midstream and Downstream Urban Agglomeration.

Figure 3 shows the changes in ESV data for six periods in different cities, and the differences in ecosystem service value (ESV) data among different cities are significant. As regional ecological pioneers, major cities such as Hangzhou, Nanjing, and Nantong are highly forward-looking, investing heavily in wetland restoration and forest maintenance to create ecological barriers and conserve water sources for cities. They also integrate resources to promote diversified green industries such as ecological agriculture and environmental protection technology, deeply integrating ecology and economy, and achieving rapid growth in ESV; Shanghai and Suzhou, with strong funds, top-notch technology, outstanding talents, and scientific planning and fine control, are able to cope with the contradictions of pollution, expansion, and protection in urbanization with ease. ESV fluctuates occasionally but overall remains stable; Small cities such as Changzhou and Tongling have weak starting economies, limited ecological investment, a single industrial structure, and slow transformation. Although ESV has grown, for example, Changzhou has increased from 29.436 billion yuan to 44.618 billion yuan in the past decade, and Tongling has increased from 7.08 billion yuan to 21.098 billion yuan. However, compared with large cities, the growth rate is relatively flat, and the ecological value gap between cities in the region is obvious, providing reference for optimizing development strategies. Overall, major cities in the Yangtze River Delta region have shown a high growth trend in ecosystem service value, especially in economically and ecologically leading cities such as Hangzhou, Nanjing, and Nantong. Relatively speaking, the changes in some smaller cities are relatively stable, with lower growth rates, indicating differences in the value of ecosystem services among different regions.

3.3. Correlation analysis between socio-economic data and ESV

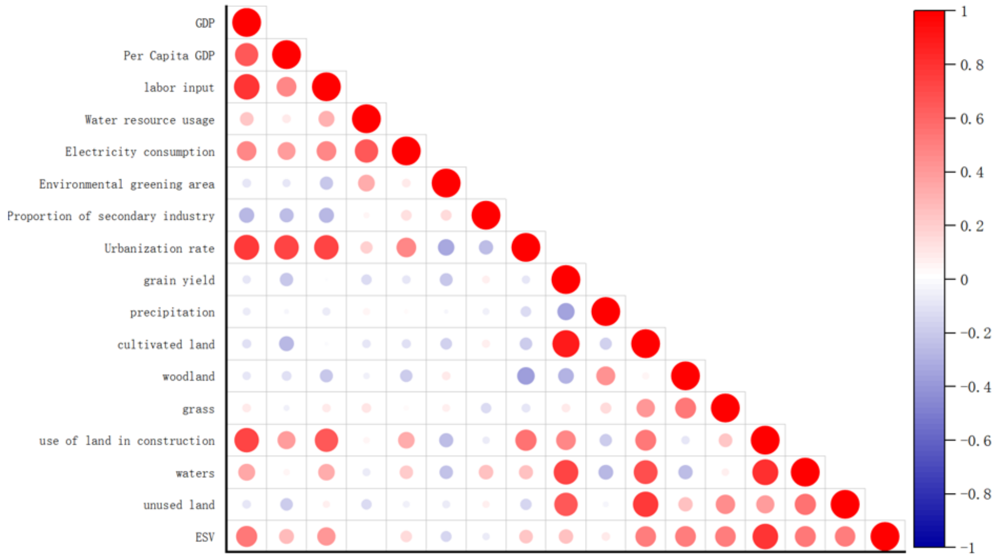

Figure 4. Correlation analysis between various elements and ESV.

In exploring the driving mechanism of ESV from a socio-economic perspective, a preliminary Pearson correlation coefficient analysis was conducted between the collected socio-economic data and ESV. Firstly, linear screening is conducted to preliminarily identify key factors related to ESV, in order to narrow down the scope of subsequent analysis. According to Figure 4, most indicators show a strong correlation with ESV, with only a strong correlation observed in electricity resource usage. However, the indicators of water resource usage, environmental green area, proportion of secondary industry, and precipitation have been determined to have relatively low correlation with ESV. In order to improve analysis efficiency and focus on key factors, they will not be considered in subsequent operations, in order to more accurately and deeply explore the intrinsic relationship between ESV and other core factors.

3.4. Driving factors of ecosystem service value

SEPI plays a key role in comprehensive and regional research, integrating significant factors, constructing comprehensive driving variables, reflecting the overall impact of socio-economic pressures, and providing key inputs for geographic detectors. Then, a geographic detector is used to combine it with SEPI to answer questions about the explanatory power of factors on the spatial distribution of ESV and regional differences, further deepening the spatial visualization and interpretation of the results.

Through the analysis of the given data results, it can be concluded that each factor exhibits different characteristics in terms of explanatory power and statistical significance for the spatial differentiation of the dependent variable. With the acceleration of urbanization, the expansion of "construction land" has greatly changed the surface morphology and ecological structure, and natural vegetation has been encroached upon. The functions of water conservation and climate regulation have been weakened, and intensive human activities have brought more waste and energy consumption, making the surrounding ecology unbearable. As a result, it is closely connected to ESV, with a q-value as high as 0.667 and an extremely low p-value; Arable land and grassland, with their unique ecological functions, can effectively regulate ESV fluctuations. Arable land carefully protects the soil, ensures crop growth, creates a home for soil organisms, and promotes a virtuous cycle of ecology. Grassland has developed root systems that solidify soil and retain water, providing a protective umbrella for wildlife and plants. The two complement each other to stabilize the ecology, thereby affecting ESV; The existence and distribution of "unused land" may affect the spatial characteristics of the dependent variable from the perspectives of maintaining ecosystem integrity and releasing potential development pressure, with a q-value of 0.385.

On the other hand, economic factors such as "GDP" are inadequate in explaining ESV, as traditional economic growth emphasizes economy over ecology, industrial adjustments tend to focus on high energy consuming and high polluting areas, and changes in resource flows indirectly interfere with ESV, resulting in p-values exceeding the statistical standard of 0.05; The use of "electricity resources" is mostly used for energy consumption in production and daily life, and is indirectly related to ESV. Unlike land use, which directly reshapes the ecology, the impact is weak, with low q values and high p values; The "urbanization rate" focuses on population aggregation and infrastructure construction, but lags behind in ecological protection when driving the economy, making it difficult to dominate the direction of ESV; The 'grain yield' is constrained by local climate and soil fertility, and fluctuations are difficult to affect the ESV macro pattern, with loose connections and a q value of 0.072; The q-value of "water area" is 0.320. Due to its functions in water resource supply, aquatic ecosystem services, etc., water area has a certain explanatory power for the spatial differentiation of the dependent variable, but it does not reach a significant level in statistical significance.

4. Conclusion

The traditional assessment of ecosystem service value (ESV) often focuses on natural ecological factors, but the role of socio-economic factors can not be underestimated, which has a profound impact on the dynamic changes of ESV, but has not been fully explored. This study focuses on the urban agglomerations in the middle and lower reaches of the Yangtze River, breaking through the Convention and innovatively taking the socio-economic perspective as the core entry point. The data of 16 key indicators of 26 cities in 6 phases from 2010 to 2020 were systematically integrated. Based on the evaluation of ESV by using the advanced equivalent factor method, the social and economic pressure index (SEPI) was constructed for the first time, which was used as the key input of the geographical detector to deeply explore the relationship between it and ESV. This study not only improves the understanding of the dynamic changes of ESV, but also provides a new direction for future research, that is, to further accurately quantify the relationship between socio-economic factors and ESV. In addition, under the background of the rapid development of urbanization, the guiding role of regional ecological protection and land use policy system is the key aspect of the application feasibility of this study.

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