frontiers | Frontiers in Earth Science

TYPE Original Research
PUBLISHED 02 October 2024
DOI 10.3389/feart.2024.1432037

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OPEN ACCESS

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RECEIVED 13 May 2024
ACCEPTED 23 September 2024
PUBLISHED 02 October 2024

CITATION
Lei M, Ma G, Yu F, Tang Z, Yang W, Zhou Y and Peng F (2024) Study on the ecosystem service flow based on the relationship of between supply and demand in Yangtze River Economic Belt.
Front. Earth Sci. 12:1432037.
doi: 10.3389/feart.2024.1432037

Study on the ecosystem service flow based on the relationship of between supply and demand in Yangtze River Economic Belt

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Ecosystems supply goods and services to humans and are the basis for sustainable development of human society. The study of the supply of ecosystem services and the demand and consumption of ecosystem services by human society, and the analysis of the supply and demand characteristics and flow relationships of ecosystem service flows are of great significance for the management of regional ecosystems and the development of ecological compensation. Taking the Yangtze River Economic Belt as an example, this paper calculates the supply and demand indices of ecosystem services in 2015 and 2020, and determines the ecosystem spatial flow paths and flow volumes from the ecosystem supply area to the demand area based on various methods and models such as the minimum cumulative resistance (MCR) model and distance decay model. The results indicate that 1). In 2015 and 2020, the supply and demand of ecosystem services in the Yangtze River Economic Zone show an increasing trend numerically, and there is spatial heterogeneity in the spatial distribution. In terms of ecosystem service supply per unit area, the midstream region is higher than the upstream and downstream regions. In terms of the demand for ecosystem services per unit area, the downstream is higher than the midstream and upstream. 2). From the supply-demand balance of ecosystem services in the Yangtze River Economic Zone, the midstream region is mainly the area of surplus supply of ecosystem services, and the downstream region is mainly the area of deficit supply. From 2015 to 2020, the number of areas with balanced supply and demand of ecosystem services in the Yangtze River Economic Belt decreases and the number of areas with unbalanced supply and demand increases, which is related to the changes in the level of economic development and land use patterns. 3). The flow of ecosystem services in the Yangtze River Economic Belt shows an increasing trend, from 726.59 billion yuan in 2015 to 1,450.54 billion yuan in 2020, with Jiangxi Province being the main ecosystem service supply area and Zhejiang Province being the main ecosystem service demand area in the Yangtze River Economic Belt.

KEYWORDS

Yangtze River Economic Belt, ecosystem service values (ESVs), supply and demand relationship, ecosystem service flow, ecological compensation

1 Instruction

Ecosystems provide a variety of goods and services to humans through ecological processes and functions, and are the basis for the survival and development of human society. Since the 1990s, the study of ecosystem services has gradually become a hot spot and a frontier in geography and ecology, and international organizations have been promoting a series of large-scale studies on ecosystem value accounting (Reid et al., 2005; Brink et al., 2009; United Nations, European Commission, Organisation for Economic Co-Operation and Development, and World Bank Group, 2021). With the practice of "two mountains" theory and Xi Jinping's thought of ecological civilization in China, the research on ecosystem service value accounting in China has set off a boom, which has led to a new period of ecosystem service value accounting from theoretical discussion to practical application in China (Lu et al., 2004; Ouyang et al., 2020; Xie et al., 2015; Ma G. X. et al., 2017; Zhang et al., 2019; Ma et al., 2020). In the new period of practical application, how to design ecological compensation policy based on ecosystem service value accounting has become the focus of attention, but the existing studies are mainly from the perspective of ecosystem service supply, and the supply-flow-demand relationship of ecological services is not sufficiently studied (Zhao et al., 2021), and the mechanisms of ecological service beneficiary objects, spatial spillover range and spillover value amount cannot be fully portrayed, which affects the policy application of ecosystem service accounting.

Currently there is no harmonized formulation of the definition for demand of ecosystem services. Demand in economics is the quantity of a good that a consumer is willing to buy at various price levels over a certain period of time, and the consumer's desire and ability to buy are the basic factors that constitute effective demand. Whereas ecosystem services are the benefits that human beings obtain directly or indirectly from ecosystems, ecosystem services are intangible and unpaid public goods, so ecosystem services that are perceived by consumers and generate utility can constitute effective demand. Therefore, the demand for ecosystem services considered in this paper is the quality and quantity of ecosystem services demanded or desired by society (Villamagna et al., 2013; Schröter et al., 2014); the supply of ecosystem services is the natural resources and services provided by ecosystems that can be physically utilized within a given time and regional context (Burkhard et al., 2012); supply and demand of ecosystem services are characterized by strong temporal and spatial differentiation (Termansen et al., 2013). The supply of ecosystem services is limited spatially by the spatial distribution of land use types and quantitatively by the capacity of natural capital to provide services. The demand of ecosystem services, on the other hand, is determined by the socio-economic activities of individuals and groups, with regional variability, and regions with different degrees of dependence on natural resources present different demand targets. Economically backward regions have the greatest demand for the most basic food and energy supply services, while urban residents are more concerned with subjective needs and ecological wellbeing.

Ecosystem service flow is the dynamic process of a certain service with mobility and transmission in different spatial regions within a certain time scale (Bagstad et al., 2013), reflecting the dynamic process of flow of ecosystem services from natural ecosystems to human social systems. Ecosystem service flows reveal the differences in ecosystem service supply and demand by identifying the supply and demand areas of ecosystem services, reflect the spatial allocation of environmental resources, and play an important role in studying the formation, transport, transformation and maintenance of ecosystem services (Ma L. et al., 2017). Ecosystem service flow have three attributes: flow direction is the direction of ecosystem service transfer from the supply area to the demand area, the flow rate of ecosystem service flow is the ratio of ecosystem service transfer distance to transfer time, and the flow rate of ecosystem service is the amount of ecosystem service received by the beneficiary area. The transmission of ecosystem services from the supply area to the beneficiary area basically follows the law of distance decay, as the distance between the supply area and the beneficiary area increases, the flow of ecosystem services received by the beneficiary area decreases (Bagstad et al., 2013; Liu H. M. et al., 2016), the determination of ecosystem service flow is the fundamental part of quantitative ecosystem service flow (Liu et al., 2017). The essence of ecosystem service flows is to establish spatial and temporal correlations between ecosystem service supply and demand areas, to clarify when and where the benefits generated by ecosystem services are enjoyed, and to provide useful information for the development of ecological compensation standards. Therefore, ecosystem service flow research is a synthesis and extension of current research on ecosystem service value assessment, trade-off synergy and its spatial heterogeneity (Wang and Zhou, 2019), and the quantification and spatialization of ecosystem service supply and demand, supply and demand balance, and spatial distribution of supply and demand have become hot issues in international ecosystem service research (Wu et al., 2019; Lorilla et al., 2019; Wang et al., 2019; Xu et al., 2021).

Taking the Yangtze River Economic Belt as the research area, this paper constructs a spatial flow model of ecosystem services, clarifies the transfer process of ecosystem services between natural systems and human social systems, identifies the supply and demand areas of the ecosystem in the Yangtze River Economic Belt, reveals the transmission path and spatial effects of ecosystem services, and analyzes the spatial-temporal changes of the "source and sink" areas and flow volume of the ecosystem in the Yangtze River Economic Belt. Scientific research and judgment on the scope and value of spatial spillover of ecosystem services will provide scientific basis for policy formulation of ecological compensation in the Yangtze River Economic Belt.

2 Research methods and data sources

2.1 Study area

The Yangtze River Economic Belt (Figure 1) spans three major regions of China, east, west, and central, with an area of about 2, 052, 300 km^2, accounting for 21.4% of China's land area, and its population and regional GDP both exceed 40% of the country. The upper reaches include Chongqing, Sichuan, Guizhou, and Yunnan, with an area of 1,137,400 km^2, accounting for 55.4% of the Yangtze River economic belt; The middle reaches include Jiangxi, Hubei, and Hunan provinces, with an area of about 564,600 km^2, accounting for 27.5% of the Yangtze River Economic Belt; The downstream region includes Shanghai, Jiangsu, Zhejiang and Anhui provinces and cities, with an area of about 350,300 km^2, accounting for 17.1% of the Yangtze River Economic Belt. The Yangtze River Economic Belt is one of the

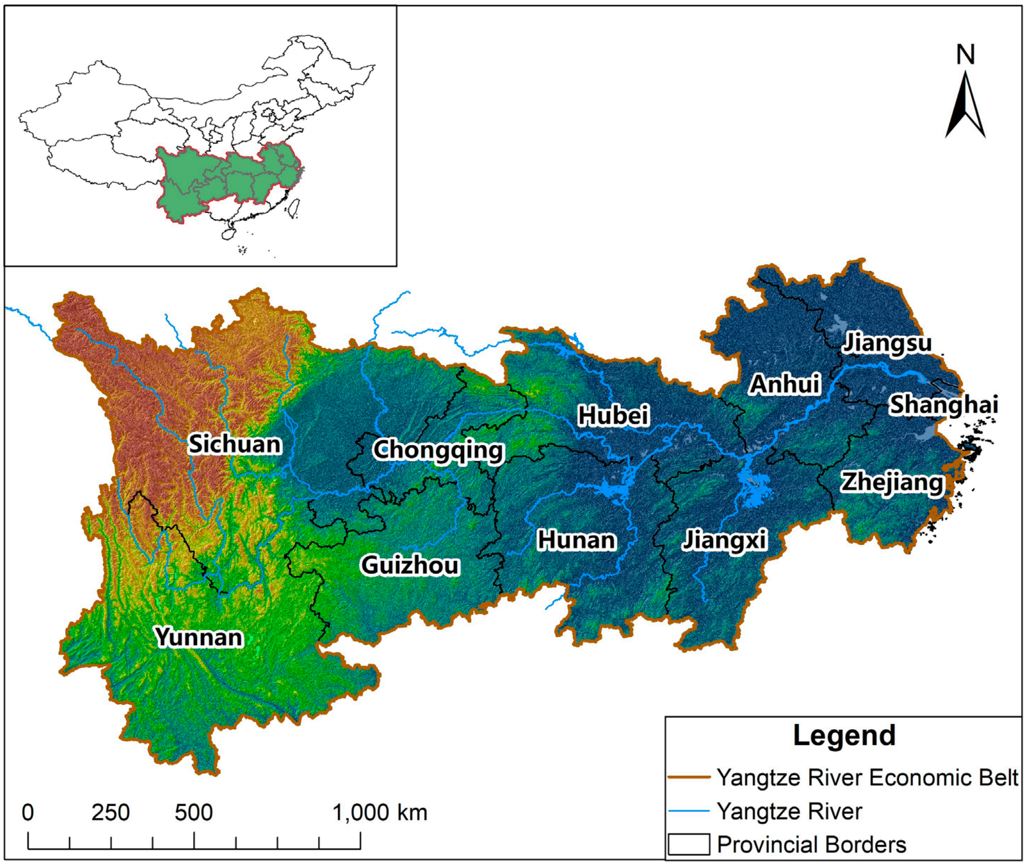

FIGURE 1
Study area.

"three major strategies" that China focuses on implementing. It is the inland river economic belt with global influence, the coordinated development belt of interaction and cooperation between the East and the West, the comprehensive promotion of the opening up belt to the outside world along the coast and the border, and the leading demonstration belt of ecological civilization construction.

According to the National Survey and Assessment Report on Changes in Ecological Conditions (2015–2020), China's ecological conditions are generally stable and improving in 2015–2020. In order to clarify the ecological compensation relationship among the provinces in the Yangtze River Economic Belt in the context of overall ecological improvement, further explore the defects and deficiencies of the theory of ecosystem service flow, sound the methodological and theoretical system, and lay the foundation for further practical application in the future, this study chooses the Yangtze River Economic Belt in 2015–2020 as the study area to carry out the study of ecosystem service flow.

2.2 Method

2.2.1 Ecosystem services value accounting

Ecosystem services include three major services: supply services, regulation services, and cultural services, among which regulation services include more than 10 indicators, such as carbon sequestration and oxygen release, soil conservation, water conservation, flood regulation and storage, climate regulation, wind protection and sand fixation, etc., but not all these indicators are mobile and can bring ecological benefits to other regions. Combined with the regional characteristics of the Yangtze River Economic Belt, this paper only performs value accounting for the indicators of ecosystem services with mobility and public good attributes, such as carbon sequestration and oxygen release, water conservation, flood regulation and storage, soil conservation, and climate regulation (Table 1), and the specific calculation method can be found in the author's article published in China Environmental Science (Ma L. et al., 2017).

2.2.2 Demand index for ecosystem services

In this paper, we quantify the demand for ecosystem services by calculating the value of ecosystem services that human society can obtain or hope to obtain (Baró et al., 2016), and considering the influencing factors of ecosystem service demand and the availability of data (Gu et al., 2018), we select four indicators: population density, GDP per unit area (Xu et al., 2021), land use intensity and UEL (Gu et al., 2019) to comprehensively reflect the demand for ecosystem services.

$$D = d_{i1} \times \lg(d_{i2}) \times \lg(d_{i3}) \times \lg(d_{i4}) \quad (1)$$

In Equation 1: D is Demand index for ecosystem services of the assessment unit; d_{i1} is Population density (10,000 people/km^2); d_{i2} is GDP/unit area (million yuan/km2); d_{i3} is Land use intensity, calculated as a percentage of total land area for construction; d_{i4} is UEL, A comprehensive indicator of urban expansion, calculated using night light data.

2.2.3 Identification of supply area and demand area for ecosystem services

In this paper, the ratio of supply and demand of ecosystem services is used to link the potential supply of ecosystem services with the potential demand of human beings (Liu L. C. et al., 2019), and based on the ratio of supply and demand of ecosystem services, the spatial agglomeration degree (R_i^*) of the R value of the supply and demand ratio is analyzed by using the hot spot analysis (Getis-Ord Gi*) function in the ArcMap toolbox to obtain the actual supply area and demand area of ecosystem services. When R_i^* is 0, it means that R has not clustered, which is the supply and demand balance area; R_i^*>0, supply surplus area, R_i^* <0, supply deficit area.

$$R_i = \frac{S_i - D_i}{(S_{max} + D_{max})/2} \tag{2}$$

$$R_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2}{n-1}}} \tag{3}$$

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{4}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2} \tag{5}$$

In Equations 2–5: R_i is the ratio of supply and demand of ecosystem services for the i patch; S_i and D_i is the value and demand indices of ecosystem services in the i patch, and the normalization method was used to standardize the value and demand indices of ecosystem services. S_{max} is the maximum supply of ecosystem services; D_{max} is the maximum demand for ecosystem services. R_i^* is the hot spot analysis of R_i, j is all features in the neighborhood of the i patch, x_j represents the attribute value of the jth feature in the neighborhood, $w_{i,j}$ represents the spatial distance between features i and j, and n is the total number of features in the neighborhood.

2.2.4 The best flow path of ecosystem services

The identified supply surplus area is judged as ecosystem service supply area, and the supply deficit area is judged as ecosystem service demand area, the minimum cumulative resistance model (MCR) is used to study the potential path of ecosystem service flow, and the gravity model is further used to calculate the interaction force matrix between the ecosystem service supply area and the demand area to determine the ecosystem service flow path.

$$G_{a,b} = \frac{N_a N_b}{D_{ab}^2} = \frac{\left[\frac{1}{P_a} \times \ln(S_a)\right]\left[\frac{1}{P_b} \times \ln(S_b)\right]}{\left(\frac{L_{ab}}{L_{max}}\right)^2} = \frac{L_{max}^2 \ln(S_a)\ln(S_b)}{L_{ab}^2 P_a P_b} \tag{6}$$

In Equation 6: G_{ab} is the interaction force between the ecosystem service supply area and the ecosystem service demand area; N_a and N_b are the weight values of the two regions respectively; D_{ab} is the normalized value of potential flow path resistance between a and b; P_a is the resistance value of region a, and S_a is the area of region a (km^2); L_{ab} is the cumulative resistance value of the flow path between a and b; L_{max} is the maximum value of the cumulative resistance of all flow paths in the study area.

2.2.5 The flow of ecosystem services

The value of ecosystem services has a certain regional and directional nature, and the value flow basically follows the law of distance attenuation (Qiao et al., 2017). The fracture point formula was used to simulate the boundary of the flow of ecosystem service value from the ecosystem service supply area to the ecosystem service demand area, and the flow intensity of ecosystem services per unit area was calculated according to the field strength theory (Chen et al., 2014), and finally the flow amount from the ecosystem service supply area to the ecosystem service demand area was obtained.

$$E_{s,d} = I_{s,d} A k_{s,d} \tag{7}$$

$$I_{s,d} = \frac{E_s}{D_{s,d}^2} \tag{8}$$

$$A = D_s^2 \pi \tag{9}$$

TABLE 1 Indicators of ecosystem services and accounting methods.

Ecosystem service indicators	Accounting methods	Value-accounting methods
Carbon sequestration and oxygen release	Net ecosystem productivity method	Market value
Water conservation	Water balance method	Replacement cost method
Flood regulation and storage	Water storage model	Replacement cost method
Soil conservation	Revised universal soil loss equation (RUSLE)	Replacement cost method
Climate regulation	Dissipation model	Replacement cost method

$$D_s = \frac{D_{s,d}}{1 + \sqrt{E_s/E_d}} \tag{10}$$

In Equations 7–10: $E_{s,d}$ is the flow amount from the ecosystem service supply area to the ecosystem service demand area. $I_{s,d}$ is the flow intensity of ecosystem services from the ecosystem service supply area to the ecosystem service demand area (10,000 yuan/km^2); A is the radiation area of ecosystem services from the ecosystem service supply area to the ecosystem service demand area (km^2); $k_{s,d}$ is the spatial flow influence factor of ecosystem services affecting the ecosystem service supply area to the ecosystem service demand area, influenced by flow factors such as water flow, wind speed and wind direction, taking values in the range of [0, 1], which in this case is 0.6 (Reynolds et al., 2010); D_s is the distance between the center of mass and the fault point (km) in the ecosystem service supply area; $D_{s,d}$ is the distance between the center of mass of the ecosystem service supply area and the center of mass of the ecological demand area (km); E_s and E_d are the value of ecosystem services in ecosystem service supply area and demand area, respectively (10,000 yuan).

2.3 Data resource

The research data are: 1) The meteorological data were obtained from the China Surface Climate Data Daily Dataset (V3.0), selected from the national reference and basic stations in 11 provinces of the Yangtze River Economic Belt, spanning the period from January 1 to 31 December 2015 and January 1 to 31 December 2020, and selected meteorological parameters such as 20–20 h cumulative precipitation, daily maximum temperature, daily minimum temperature and hourly average wind speed data from each station Data. The data were obtained from the China Meteorological Data Network (http://data.cma.cn). 2) The land use data is derived from the national land use remote sensing monitoring data with a resolution of 1 km released by the Resource and Environmental Science Data Center of the Chinese Academy of Sciences for the 2 years of 2015 and 2020. 3) The night light data is derived from the 2012–2020 Annual VNL V2 global annual light dataset released by NOAA/NGDC's Earth Observation Group (EOG). 4) Net primary productivity (NPP) of vegetation is derived from NASA EOS/MODIS's MOD17A3 global annual NPP data product. 5) The normalized vegetation index (NDVI) comes from the MOD13Q1 global 16-day NDVI data product of NASA EOS/MODIS. 6) The soil data is derived from the 1:4,000,000 Chinese soil map dataset released by the Nanjing Institute of Soil Science, Chinese Academy of Sciences. 7) The spatial distribution data of population is derived from the China's population spatial distribution kilometer grid dataset released by the Resource and Environmental Science Data Center of the Chinese Academy of Sciences, and the time scale is yearly. 8) The spatial distribution data of GDP is derived from the grid dataset of the spatial distribution of China's GDP in kilometers released by the Resource and Environmental Science Data Center of the Chinese Academy of Sciences.

3 Result

3.1 Research on ecosystem service supply area and demand area in the Yangtze River Economic Belt

3.1.1 Spatial-temporal characteristics of ecosystem service supply in the Yangtze River Economic Belt

The ecosystem service flows are mainly influenced by the intensity of ecosystem service radiation, i.e., the value of ecosystem services per unit area. In 2015 and 2020, the value of ecosystem services per unit area in the Yangtze River Economic Belt was 78,400 RMB/km^2 and 102,800 RMB/km^2, respectively (Figure 2), and the value of ecosystem services in the Yangtze River Economic Belt generally increased except for Fuyang, Bozhou and Suzhou in Anhui Province. From the perspective of the value of ecological services per unit area, the value of ecosystem services in the Yangtze River Economic Belt shows the spatial characteristics of high in the east and low in the west, and the high value is mainly concentrated in Hubei, Hunan, Jiangxi and Anhui, and is generally distributed around Dongting Lake, Poyang Lake and Taihu Lake. Most of the land use types in this area are forest land and water, with good ecological background and strong ecosystem service capacity per unit area. The water area of Xiantao City, Hubei Province accounts for 30.52% of the city's area, and the value of climate regulation and flood regulation and storage services is high, and the value of ecosystem services per unit area in 2015 and 2020 is 281,300 yuan/km^2 and 316,400 yuan/km^2, respectively, which is the prefecture and city unit with the highest value of ecological services per unit area in the Yangtze River Economic Belt. The low value of ecosystem services per unit area is mainly distributed in Sichuan, Yunnan, and Guizhou, and a small amount was also distributed in Anhui and Jiangsu Province. The lowest value of ecosystem services per unit area is Suzhou City, Anhui Province, where the value of ecosystem services in 2015 and 2020 is 19,200 yuan/km^2 and 17,500 yuan/km^2, and the land use type is mainly cultivated land.

3.1.2 Spatial-temporal characteristics of demand for ecosystem services in the Yangtze River Economic Belt

In 2015 and 2020, the average demand index for ecosystem services in the Yangtze River Economic Belt was 1.9 and 2.6. The demand for ecosystem services in the study area generally increased, and while demand index in Shanghai, Suzhou, Wuxi, Nanjing, Jiaxing and Chengdu increased significantly (Figure 3). The demand for ecosystem services in the Yangtze River Economic Belt is closely related to the level of urban development, with obvious differences between cities and cities, showing the spatial characteristics of high east and low west, and high demand for ecosystem services is mainly concentrated in Jiangsu, Zhejiang, Anhui, and other regions, which are densely populated, have a high level of economic development, with high demand for ecosystem services. The highest demand area for ecosystem services is Shanghai, with a demand index of 19.9 and 27.7 in 2015 and 2020, respectively. The low-demand areas for ecosystem services were mainly distributed in underdeveloped prefectures and cities in

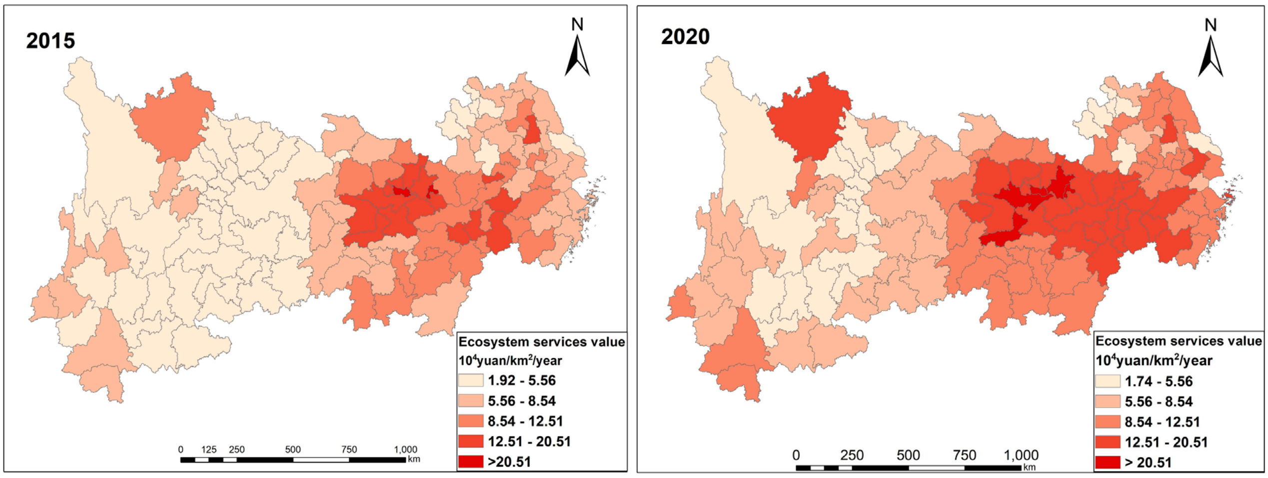

FIGURE 2
Value of ecosystem services in 2015 and 2020 (10,000 yuan/km^2).

western Sichuan, southern Hunan, Yunnan and Guizhou, and the lowest demand areas were Ganzi Tibetan Autonomous Prefecture, with ecosystem service demand indices of 0.001 and 0.003 in 2015 and 2020, respectively. Ganzi Tibetan Autonomous Prefecture is located in the transition zone from China's first step to the second step of the Yunnan-Guizhou Plateau and the Sichuan Basin, belongs to the northern section of the Hengduan Mountain System in the western Sichuan Alpine Plateau. Ganzi Tibetan Autonomous Prefecture is the second largest Tibetan area in China, but also the core area of Khamba, the land is sparsely populated, the economy is relatively backward. In 2020, the GDP per unit area is 263,300 yuan/km2, the built-up area is 0.07%, the population density is 127 people/km^2, and the lighting index UEL is only 28.4, which is limited by geographical conditions, the degree of land development is insufficient, and the indicators are far below the average.

3.1.3 Analysis of supply and demand of ecosystem services in the Yangtze River Economic Belt

From 2015 to 2020, the supply-demand ratio of the Yangtze River Economic Belt generally increased, among which Hubei, Hunan, southern Anhui, Jiangxi and other regions formed areas with high supply-demand ratios, and the imbalance between supply and demand of ecosystem services in the Yangtze River Delta, northern Anhui and northern Jiangsu further intensified. Based on the ratio of supply and demand, the analysis of hot spot analysis was used to analyze the supply surplus area and supply deficit area of ecosystem services in the Yangtze River Economic Belt. The red in Figure 4 shows the supply deficit areas where the supply of ecosystem services is less than the demand, mainly distributed in all of Jiangsu Province, northern Zhejiang Province, eastern and northern Anhui Province, and Shanghai City, the end of the Yangtze River Economic Belt, these areas are densely populated, economically developed, with a high level of urbanization development, and the growing demand for ecosystem services far exceeds the value output of ecosystem services in the region. The green area in Figure 4 is a supply surplus area where the supply of ecosystem services exceeds the demand, distributed mainly in Hubei Province, Hunan Province and Jiangxi Province in the middle reaches of the Yangtze River Economic Belt, which has a high level of ecosystem service value per unit area and occupies the first echelon within the Yangtze River Economic Belt. Grey is the supply and demand balance area, mainly distributed in the upper reaches of the Yangtze River Economic Belt, concentrated in Sichuan, Yunnan and Guizhou provinces, among which, although Aba Prefecture and Kardze Prefecture have relatively high ecosystem service value per unit area, due to the low value of ecosystem services in surrounding prefectures and cities, they have not been able to form agglomeration in hot spot analysis, and are still supply and demand balance areas. From 2015 to 2020, the supply surplus area in the middle and lower reaches of the Yangtze River Economic Belt increases and the supply deficit area decreases, but in the upper reaches, with the rapid economic development of the Chengdu-Chongqing region, a deficit area with Chengdu as the core is formed.

3.2 Study on the spatial flow paths and flows of ecosystem services in the Yangtze River Economic Zone

3.2.1 Spatial flow paths of ecosystem services

The ecosystem service supply surplus area is the ecosystem service supply area, and the ecosystem service supply deficit area is the ecosystem service demand area. The spatial flow path of ecosystem services is an important channel connecting the ecosystem service supply area and the demand area, and is the main carrier of material exchange and energy flow in the region. In 2015, there is one ecosystem service supply area in the Yangtze River Economic Belt, mainly in Hubei, Hunan, Jiangxi and southern Anhui, and two ecosystem service demand areas, mainly in the downstream areas of Chengdu and the Yangtze River Delta. The

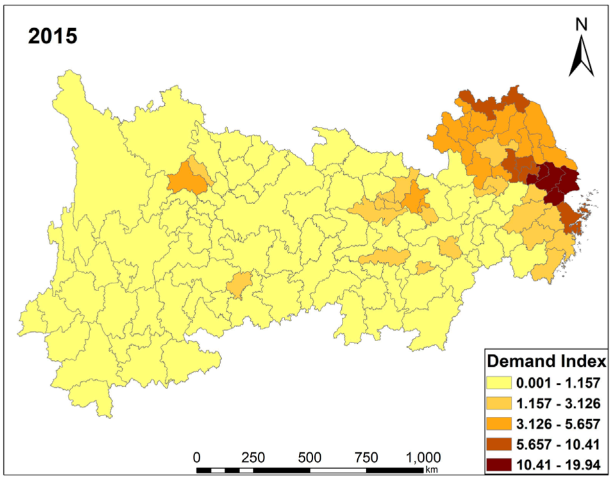

FIGURE 3
Demand for ecosystem services in 2015 and 2020.

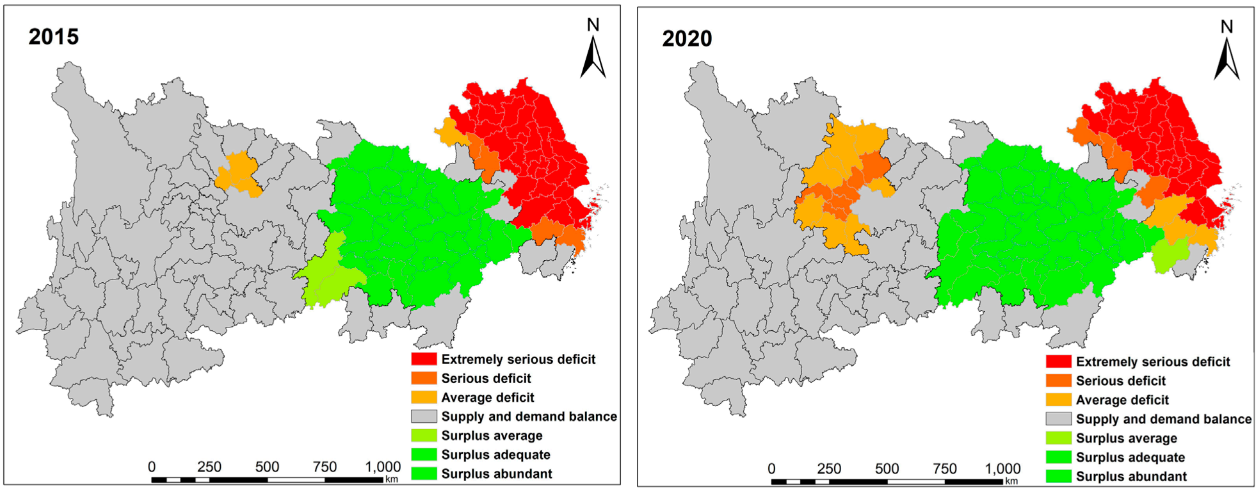

FIGURE 4
Map of supply and demand of ecosystem services, 2015 and 2020.

ecosystem service supply area in 2020 is similar to the distribution in 2015, but the ecosystem service demand area has been expanded in the middle reaches of the Yangtze River Economic Belt around Chengdu City, and the area has increased significantly compared with that in 2015. Several potential spatial flow paths between ecosystem service supply and demand areas were generated by the minimum cumulative resistance model (MCR), and in order to identify the paths with the highest possibility of ecosystem service flow, the interaction force matrices between ecological patches in 2015 and 2020 were further calculated using the gravity matrix (Figures 5, 6), and threshold criteria were set (interaction force > 9, supply and demand ratio R > 0.2), and 36 and 64 optimal spatial flow pathways were screened in 2015 and 2020, respectively, and the corresponding ecosystem service supply areas and ecosystem service demand areas were obtained. The optimal spatial flow path of ecosystem services effectively connects ecosystem service demand areas with ecosystem service supply areas, and is the link between ecosystem service supply areas and ecosystem service demand areas.

3.2.2 Flow of ecological service value in Yangtze River Economic Zone

The flow of ecosystem services from the ecosystem service supply area to the demand area of the Yangtze River Economic Zone in 2015 and 2020 was calculated using the breakpoint formula and field strength model. Ecosystem service flow from ecosystem service supply area in Yangtze River Economic Belt is 726.59 billion yuan in 2015 and 1,450.54 billion yuan in 2020. Jiangxi Province is the main ecosystem service supply area in the Yangtze River Economic Belt, mainly from Shangrao, Fuzhou, Jiujiang,

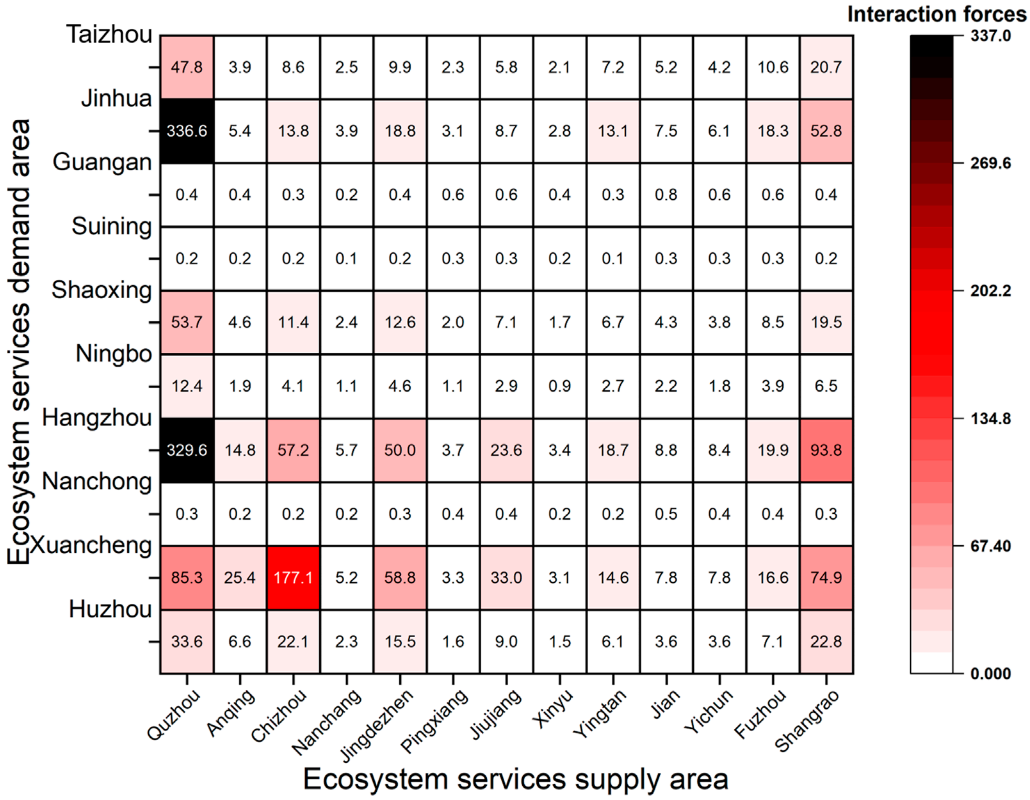

FIGURE 5
Interaction force matrix of ecological patches in 2015.

Jingdezhen and Yingtan cities, etc. (Figures 7, 8). In 2015 and 2020, the ecosystem service flow in Jiangxi Province is 525.03 billion yuan and 665.09 billion yuan, respectively, with a growth rate of 26.7%. Hangzhou is the main ecosystem service demand area in the Yangtze River Economic Belt, and the ecosystem service inflow in Hangzhou is 256.03 billion RMB in 2015 and 367.72 billion RMB in 2020, and the ecosystem service inflow is about 22% of its GDP (Figure 9). The ecosystem service inflow of Hangzhou mainly comes from Shangrao, Fuzhou, and Jiujiang cities in Jiangxi Province, and the ecosystem service outflow from Jiangxi Province accounts for 63.6% of the total ecosystem service inflow of Hangzhou. Zhejiang Province is the main ecosystem service demand area in 2015, and in 2020, in addition to Zhejiang Province, some cities in Sichuan Province become the new ecological service demand area (Figure 8). The radiation intensity of ecosystem services decays as the transmission distance increases. Although Shanghai is also an ecosystem service demand area, the flow of ecosystem services from more distant areas cannot flow into Shanghai because there is no ecosystem service supply area around it, resulting in no inflow of ecosystem services to Shanghai. Therefore, ecological construction should be carried out around ecosystem service demand areas as much as possible to facilitate the flow of ecosystem services and promote ecological benefits.

4 Discussion

4.1 Research on ecological compensation policy based on ecosystem service flow

Ecological compensation is an incentive mechanism that makes ecosystem service providers willing to provide ecosystem services with externalities or public goods (Liu et al., 2018). Because of the questions of "who should pay" and "how much to buy," the formulation of ecological compensation standards has become the core issue in the implementation of ecological compensation mechanisms. At present, the research methods of ecological compensation standards mainly include the input of ecological protectors, the loss of opportunity cost, the profit of ecological beneficiaries, the restoration cost of ecological damage, the value of ecosystem services, as well as the willingness to pay method and the ecological footprint method (Liu G. H. et al., 2021). However, the most direct purpose of ecological compensation is to protect the ecosystem on which the ecosystem service function depends, so as to achieve the goal of sustainable provision of ecosystem services; therefore, the ecological services provided by ecosystems are an important scientific basis for the design of ecological compensation systems (Ouyang and Ken, 2018; Liu G. H. et al., 2019).

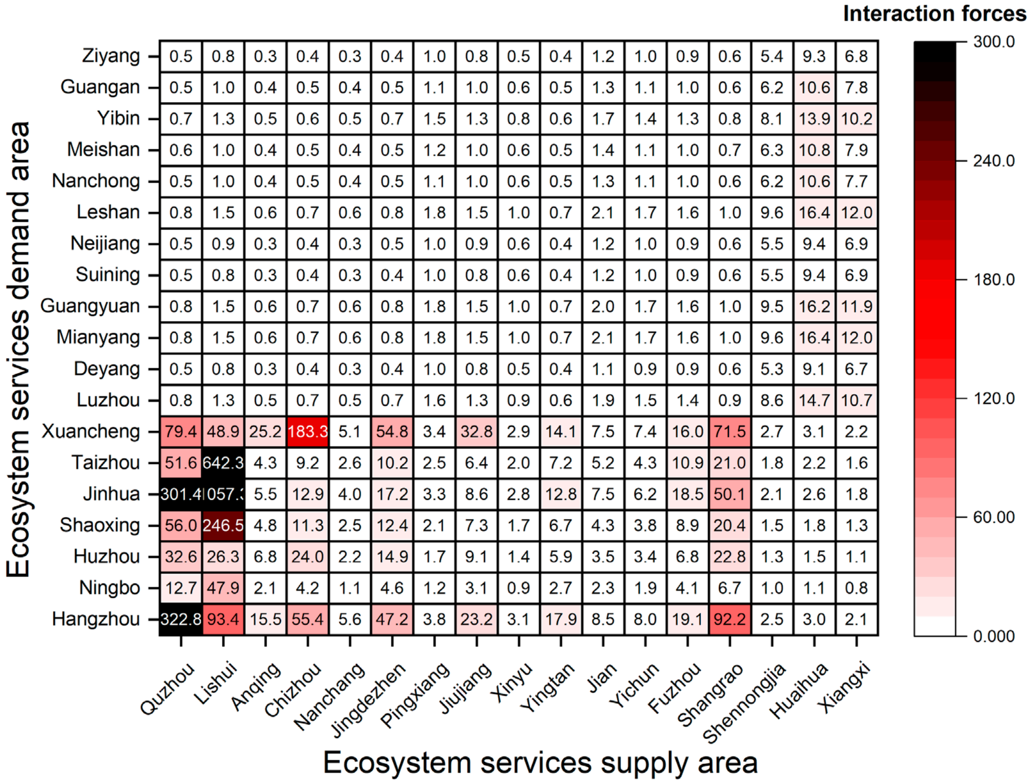

FIGURE 6
Interaction force matrix of ecological patches in 2020.

By studying the spatial distribution and spatial demand of ecosystem services, identifying the flow path of ecosystem services, and using the flow of ecosystem services as the basis of ecological compensation (Liu C. F. et al., 2021; Ma et al., 2022), we can carry out the benefit allocation between ecosystem protectors and beneficiaries and the balance mechanism of "two mountains" transformation, and promote the realization of win-win situation between economic and social development and ecological and environmental protection. Jiangxi is the main ecosystem service supply area in the Yangtze River Economic Belt, and Zhejiang is the main ecosystem service demand area in the Yangtze River Economic Belt. In 2015, the ecosystem service flow in Jiangxi province was 525.03 billion yuan, and in 2020 the ecosystem service flow was 665.09 billion yuan, an increase of 26.7%. In 2015 and 2020, the inflow of ecological services in Zhejiang Province is 536.09 billion yuan and 810.7 billion yuan, and Jiangxi Province's ecological services mainly flow to Zhejiang Province. In 2015 and 2020, the ecological service inflow from Jiangxi Province to Zhejiang Province amounted to 346.025 billion yuan and 498.87 billion yuan, mainly from Shangrao City (150.36 billion yuan in 2015 and 188.26 billion yuan in 2020), Fuzhou City (54.29 billion yuan in 2015 and 114.17 billion yuan in 2020) and Jiujiang City in Jiangxi Province (93.73 billion yuan in 2015 and 136.87 billion yuan in 2020). The main inflows were into Hangzhou City (131.42 billion yuan in 2015 and 233.91 billion yuan in 2020), Jinhua City (71.58 billion yuan in 2015 and 83.12 billion yuan in 2020), and Taizhou City (55.55 billion yuan in 2015 and 70.97 billion yuan in 2020) in Zhejiang Province. As a key forest area in the south of China, Jiangxi Province is rich in forest and wetland resources, with a stable forest coverage rate of more than 63.1%, ranking second in the country, and 13.65 million mu of wetland holdings. "During the 13th Five-Year Plan period, Jiangxi Province has completed 6.574 million mu of artificial afforestation, and the living wood accumulation has reached 685 million m^3, and the forest carbon sink capacity has been enhanced significantly. In addition, Jiangxi Province has completed wetland restoration and comprehensive management of an area of more than 75,000 mu in the Poyang Lake area, and the role of wetland carbon sinks has been further enhanced.

In 2021, the Opinions on Deepening the Reform of Ecological Protection Compensation System issued by the General Office of the Propaganda Department of CPC and the General Office of the State Council proposed to improve the horizontal compensation mechanism and promote the establishment of horizontal ecological protection compensation mechanism in the Yangtze River Basin, the initial formation of market-oriented and diversified compensation pattern based on the beneficiary pays principle, and the basic formation of a positive interaction between ecological protectors and beneficiaries. Jiangxi Province is a national ecological civilization experimental zone with outstanding ecological advantages, but the economic development level of Jiangxi Province is average, with a GDP of 2,569.15 billion yuan in 2020 and a *per capita* GDP lower than the national average. Zhejiang Province, as the main beneficiary area of Jiangxi's ecological wellbeing, should build a horizontal ecological compensation mechanism between Zhejiang Province and Jiangxi

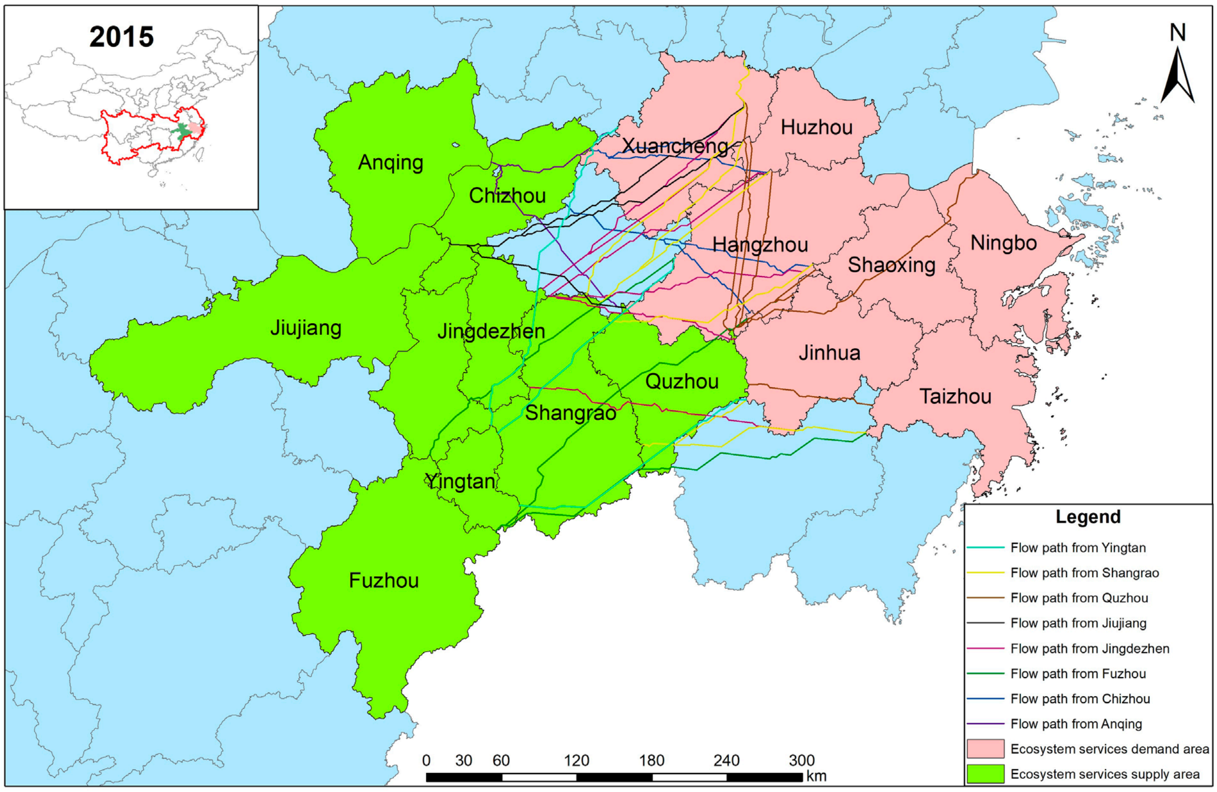

FIGURE 7
Distribution of ecological optimal spatial flow pathways, ecological service supply areas and demand areas in the study area in 2015.

Province based on the flow of ecosystem services from Jiangxi Province into Zhejiang Province, forming a benign situation where beneficiaries pay and protectors receive reasonable compensation.

4.2 Difficulties and prospects of ecosystem service flow research

Scientific knowledge of ecosystem service flows is essential for understanding the actual ecosystem service delivery and meeting human demand for ecosystem services (Wolff et al., 2015). Ecosystem service flow research connects natural ecosystems with human social systems, and the main content of its research is to explore the spatial transfer process of ecosystem services from the supply area to the demand area (Liu et al., 2017). The spatial flow of ecosystem services is a complex dynamic process, and the service flows vary differ for different spatial flow paths and different ecosystem service types. Fisher et al. (2009) classified ecosystem service flows into three categories, *in situ* service flows, all-directional service flows, and directional service flows. *In situ* service flow refers to the basic overlap between the ecosystem service generating area and the beneficiary area; all-directional service flow is the transfer of ecosystem services from the supply area to the use area along all directions; and directional service flow is the transfer of ecosystem services from the supply area to the service use area along a certain direction. Trade-off decisions for ecosystem service supply change the direction and flow of service flows, and there are complex transmission, reception, and spillover effects between different coupled human-nature systems. Therefore, ecosystem service trade-off decisions need to pay high attention to the spatial flow of ecosystem services and incorporate remote coupling of social-ecological systems in different geographic areas into the framework of decision analysis (Peng et al., 2017).

Exploring the patterns in the spatial transfer of ecosystem services is a central component in the study of ecosystem service flows (Qiao et al., 2017; Dai et al., 2016). There is a spatial mismatch between ecosystem service supply and demand, so the goods and services generated by ecosystems need to be transferred to the demand area through a spatial flow process to realize the value of their services. The transfer process is scale-dependent, with different ecosystem service types having different temporal and spatial scales. For example, services such as air purification, temperature regulation, and recreation usually act at local scales (Goldenberg et al., 2017; Vigl et al., 2017), with a relatively small scope of influence, while services such as flood storage, soil conservation, water harvesting and other services involve the transfer of services between upstream and downstream (Stürck et al., 2014; Li et al., 2017; Nedkov and Burkhard, 2021) and usually act on regional scales, and the scope of the influence of carbon sequestration services can extend to the regional, national and even global scales (Liu J. et al., 2016). Because the transfer of ecosystem services involves both natural ecological and human socio-economic systems, the transfer process is complex and influenced by multiple factors, the mechanism and law

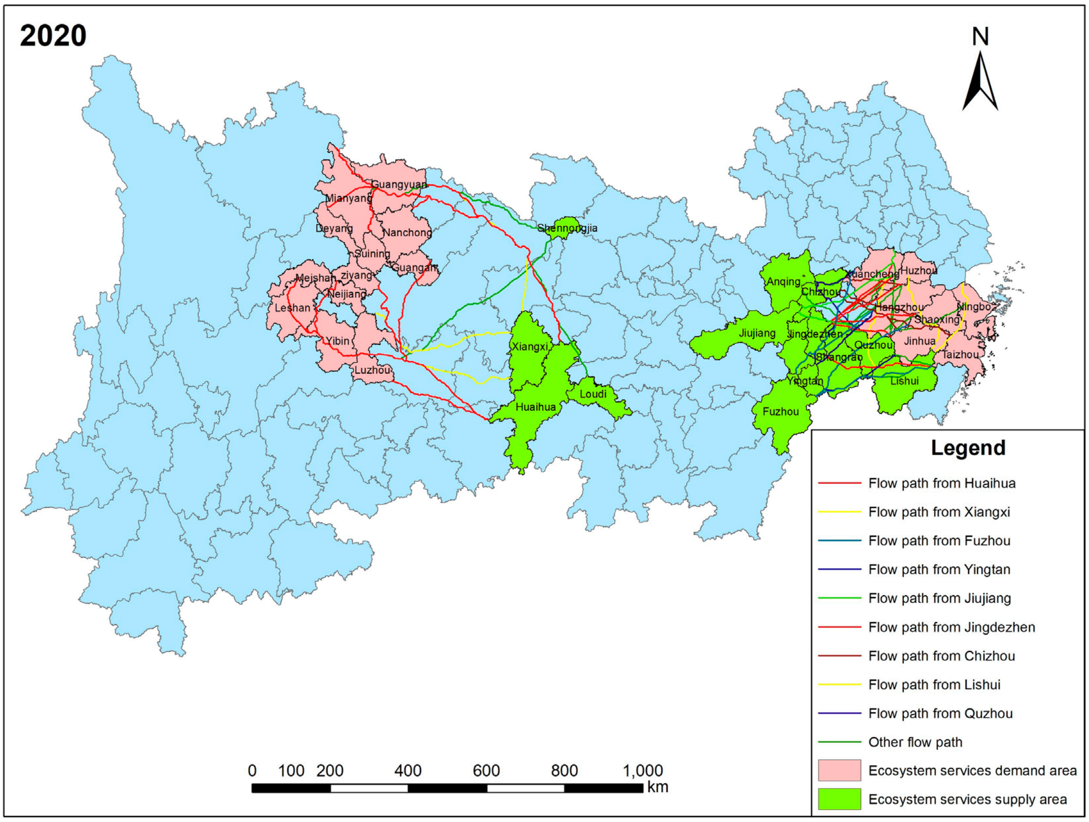

FIGURE 8
Distribution of ecological optimal spatial flow pathways, ecological service supply areas and demand areas in the study area in 2020.

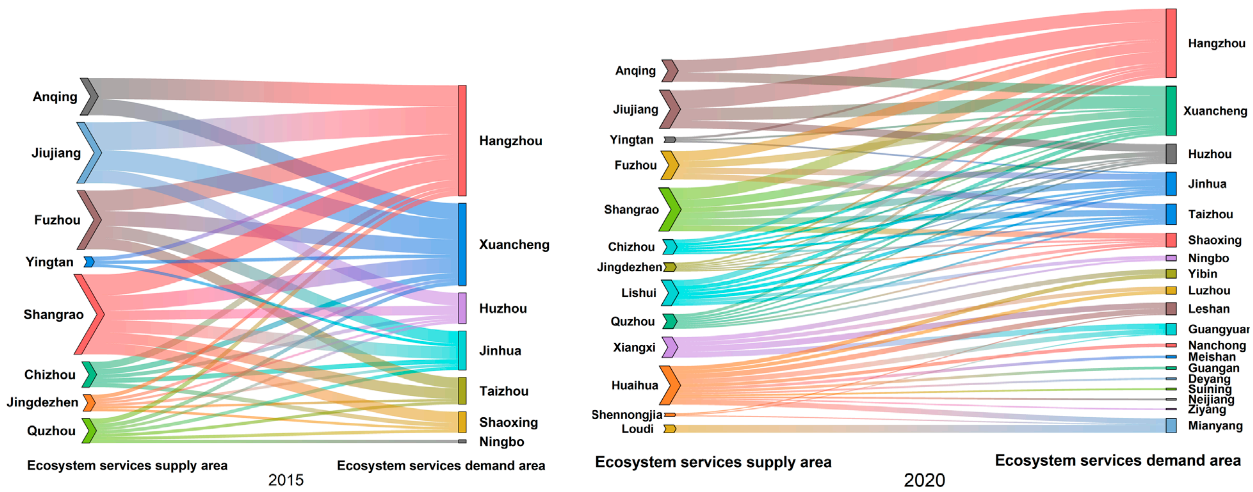

FIGURE 9
Ecological service flow from ecological service supply areas to demand areas in the Yangtze River Economic Belt in 2015 and 2020.

of the transfer of ecosystem services from supply to demand areas are not clear in current studies, and current research on ecosystem service flows mainly focuses on small scales (García-Nieto et al., 2013), lacking an understanding of the cross-scale and cross-regional characteristics of ecosystem service flows. This has limited the development of ecosystem service flow research to a certain extent (Liu et al., 2017).

Affected by the diversity and dynamics of ecosystem services, the flow of ecosystem services has the characteristics of complexity and diversity, which makes the quantitative study of ecosystem service flow a difficult problem. The existing spatialized methods for studying the supply and demand of ecosystem services mainly include four methods such as land use estimation, ecological process simulation, data spatial overlay and expert empirical discriminations (Reid et al., 2005). In this paper, the ecological model is mainly used to account for the value of ecosystem services, and the spatial flow influence factor of ecosystem services used to reflect natural influences in the assessment model adopts empirical values, the accuracy of which needs to be further improved with the in-depth research on the flow law of ecosystem services. The demand for ecosystem services in this paper is not the actual demand for ecosystem services, but a virtual demand constructed through indicators such as population, light and land use, which also affects the accurate determination of the supply and demand for ecosystem services. At present, the flow process of ecosystem services only considers geographical factors, ignoring the influence of meteorological and human factors. In the future, more parameters need to be introduced to comprehensively consider key elements that affect the heterogeneity of ecosystem service supply and demand, such as topography and landscape, vegetation, soil and land use, to determine the spatial distribution characteristics of ecosystem service suppliers and demanders and to provide accurate and specific descriptions of the path direction, flow size and decay characteristics of ecosystem service flows.

5 Conclusion

This paper identifies the ecosystem supply and demand areas in the Yangtze River Economic Belt through a spatial flow model of ecosystem services and accounts for the spatial flow of ecosystem services in the Yangtze River Economic Belt, with the following main conclusions.

(1) In 2015 and 2020, the supply and demand of ecosystem services in the Yangtze River Economic Belt increase. In terms of ecosystem service supply per unit area, the midstream region of the Yangtze River Economic Belt is higher than the upstream and downstream regions. In terms of the demand for ecosystem services per unit area, the downstream of the Yangtze River Economic Belt is higher than the midstream and upstream. The supply and demand of ecosystem services in the Yangtze River Economic Zone show spatial heterogeneity.

(2) In terms of the balance between supply and demand of ecosystem services in the Yangtze River Economic Belt, the upstream region is mainly an ecosystem service supply and demand balance area, the midstream region of Hubei Province, Hunan Province, Jiangxi Province and the southern part of Anhui Province is an ecosystem service supply-surplus area, and the downstream region of Shanghai, Zhejiang Province, Jiangsu Province, and the upstream city of Chengdu is a supply-deficit area. From 2015–2020, the number of areas with balanced supply and demand of ecosystem services in the Yangtze River Economic Belt decreases and the number of areas with unbalanced supply and demand increases, which is related to the changes in the level of economic development and land use patterns.

(3) The flow of ecosystem services in the Yangtze River Economic Belt shows an increasing trend, from 726.59 billion yuan in 2015 to 1,450.54 billion yuan in 2020. Jiangxi Province is the main ecosystem services supply area in the Yangtze River Economic Belt, and Zhejiang Province is the main ecosystem services demand area in the Yangtze River Economic Belt. The ecosystem services of Jiangxi Province mainly flow to Zhejiang Province. In 2015, the ecosystem services flow from Jiangxi Province to Zhejiang Province was RMB 346.025 billion, accounting for 65.9% of the ecosystem services flow in Jiangxi Province; in 2020, the ecosystem services flow from Jiangxi Province to Zhejiang Province was RMB 498.87 billion, accounting for 61.5%. Zhejiang Province, as the main beneficiary area of ecological wellbeing of Jiangxi Province, should build a horizontal ecological compensation mechanism between Zhejiang Province and Jiangxi Province based on the ecosystem service flow from Jiangxi Province into Zhejiang Province, forming a benign situation where beneficiaries pay and protectors are reasonably compensated.

(4) Based on their ecological properties and functions, ecosystem services provided by ecosystems are potential supplies, and only products or services actually used by humans are actual ecosystem service supplies, and the flow of ecosystem services is a reflection of the actual supply of ecosystem services. The intensity of ecosystem service radiation decays with increasing transmission distance, although Shanghai is also an ecosystem service demand area, the flow of ecological services from more distant areas cannot flow into Shanghai because there is no ecosystem supply area around it, resulting in no ecosystem service inflow to Shanghai. Therefore, ecological construction around ecosystem demand areas is conducive to the actual supply of ecosystem services, thus increasing the ecological wellbeing of humans.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

ML: Writing–original draft. GM: Funding acquisition, Writing–review and editing. FY: Conceptualization, Writing–review and editing. ZT: Methodology, Writing–review and editing. WY: Supervision, Writing–review and editing. YZ: Writing–review and editing. FP: Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. Fundamental project: National Natural Science Foundation of China (Grant No.: 42277491). Joint Study on Ecological Environment Protection and Restoration of the Yangtze River (Phase II) (Subject No.: 2022-LHYJ-02-0403).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2024.1432037/full#supplementary-material

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