STUDY ON SUSTAINABLE DEVELOPMENT EVALUATION BASED ON THE ECOLOGICAL FOOTPRINT OF GIS TECHNOLOGY IN JILIN PROVINCE, CHINA

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Abstract. GIS is capable of analyzing and processing spatial information, integrating cartographic data with conventional data to achieve visual expression and geographic analysis capabilities. Moreover, the ecological footprint serves as one of the crucial indicators for assessing the sustainable development of ecological environments at a regional level. This paper provides a comprehensive assessment of the sustainable development of Jilin Province by constructing an ecological footprint model. It analyzes the succession changes in the land ecological footprint of Jilin Province over recent years using the ecological footprint methodology. It also quantitatively examines the ecological footprint and ecological carrying capacity of Jilin Province for the years 2000, 2010, and 2020, and evaluates the sustainability of Jilin Province's ecosystem. Through data analysis, it is evident that the ecological footprint of Jilin Province has been on a continuous upward trend. Meanwhile, the region's ecological carrying capacity initially decreased before showing signs of recovery, resulting in an ecological surplus in 2000, followed by ecological deficits in 2010 and 2020. Despite these fluctuations, the sustainability of the ecosystem has shown consistent improvement. This indicates that while pressure on ecological resources is increasing, the efficiency of resource utilization is also improving. With the support of GIS technology, this study studied the sustainable development of ecological footprint in Jilin Province from 2000 to 2020, evaluated the ecosystem of Jilin Province, and established a model to provide a basis for the future research of ecological resources.
Keywords: *GIS technology, footprints, forests, grass lands, land type, land use change, water*

Introduction

In the contemporary era of globalization, the rapid advancement of the economy and science and technology in human society has been accompanied by a significant impact on the natural environment (Chakraborty and Maity, 2020). The issues of ecosystem destruction, environmental pollution, overexploitation, and resource consumption have grown increasingly prominent, placing human society in an unprecedented ecological crisis

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(Goswami, 2024). The impact and strain exerted by human activities on ecosystems have become a focal point for the international community (Denissen et al., 2022). The ecological footprint serves as a critical indicator for assessing human demand for natural resources and the sustainable development of ecosystems (Amer et al., 2024). Proposed by Rees in the 1990s, the concept of the ecological footprint quantitatively evaluates the pressure exerted on Earth's ecosystems by calculating the biologically productive land area required to support the resources consumed and the waste generated by human activities (Rees, 1990). It comprehensively accounted for the productivity disparities among various ecosystems, converting diverse resource consumptions and waste emissions into equivalent land area requirements. This methodology was refined by Wackernagel et al. offering a streamlined framework for national and global natural capital accounting (Wackernagel et al., 1999). Subsequently, scholars both of China and other countries built upon the traditional ecological footprint model (Sarkodie, 2021). They developed a balancing factor based on Net Primary Productivity (NPP) and Yield Factor (EF-NPP) to better reflect the impacts of global climate change, soil degradation, and technological advancements (Liu et al., 2018). This is model reveals the spatiotemporal evolution characteristics and influencing factors of resource consumption. Zhang and Hao employed the Global Footprint Network (GFN) calculation method in 2024 to determine the per capita ecological footprint using the productive ecological footprint approach (Zhang and Hao, 2024). In 2010, Wiedmann Thomas and Barrett John reviewed the ecological footprint methodology and proposed that the Dynamic Ecological Footprint (DEF) model is the most robust method for establishing a quantifiable relationship between human consumption, ecosystem function, and biological production (Wiedmann and Barrett, 2010). Asadkhani et al. integrated the ecological footprint with energy use and greenhouse gas emissions to assess the sustainability of rice production in Golestan province (Asadkhani et al., 2025). Ulucak and Khan (2020) study on the interplay between natural resource rents, renewable energy, urbanization, and the ecological footprint confirmed their environmental impact (Ulucak and Khan, 2020). In recent years, foreign countries have continuously refined the calculation methods of the ecological footprint, incorporating additional ecological services into the framework and conducting in-depth research across various sectors, including economic and trade dimensions (Haq et al., 2023; Xu et al., 2023). A study analyzed the dynamic and asymmetric effects of financial credit, economic growth, and technological progress on the ecological footprint of 19 selected countries in sub-Saharan Africa (Mwoya et al., 2025). By integrating ecosystem service value analysis, the ecological footprint model was enhanced to evaluate the ecological footprint and its changes within the Chengdu-Chongqing Shuangcheng Economic Circle (Li et al., 2024). The intricate relationship between financial development and the ecological footprint was also examined (Haykel, 2025). In 2021, Han et al. analyzed and forecasted the land resource carrying capacity of 31 provinces in China from 2008 to 2016, concluding that the land resource carrying capacity index of these provinces will continue to rise in the future, while land carrying capacity remains unbalanced (Han et al., 2021). The research on the ecological footprint has made significant progress in China, however, it still lags behind foreign countries (Sidi and Torii 2024). The concepts of "provincial hectare" and "municipal hectare" are tried to improve the traditional ecological footprint model to adapt to resource utilization and ecological carrying capacity analysis in different regions (Zhang et al., 2023). Therefore, considering the aforementioned facts; this study was conducted to determine impacts of GIS technology on the sustainable developmental evaluation of Jilin Province.

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Materials and methods

Geographic location and the natural environment

Geographical position

Jilin Province is located in the central part of northeast China, between 121°38’ to 131°19’ east longitude and 40°52’ to 46°18’ north latitude. The territory is 650 km long from east to west and 300 km wide from north to south, with a total area of 187,400 km^2, accounting for 2% of the country’s total area (*Figure 1*).

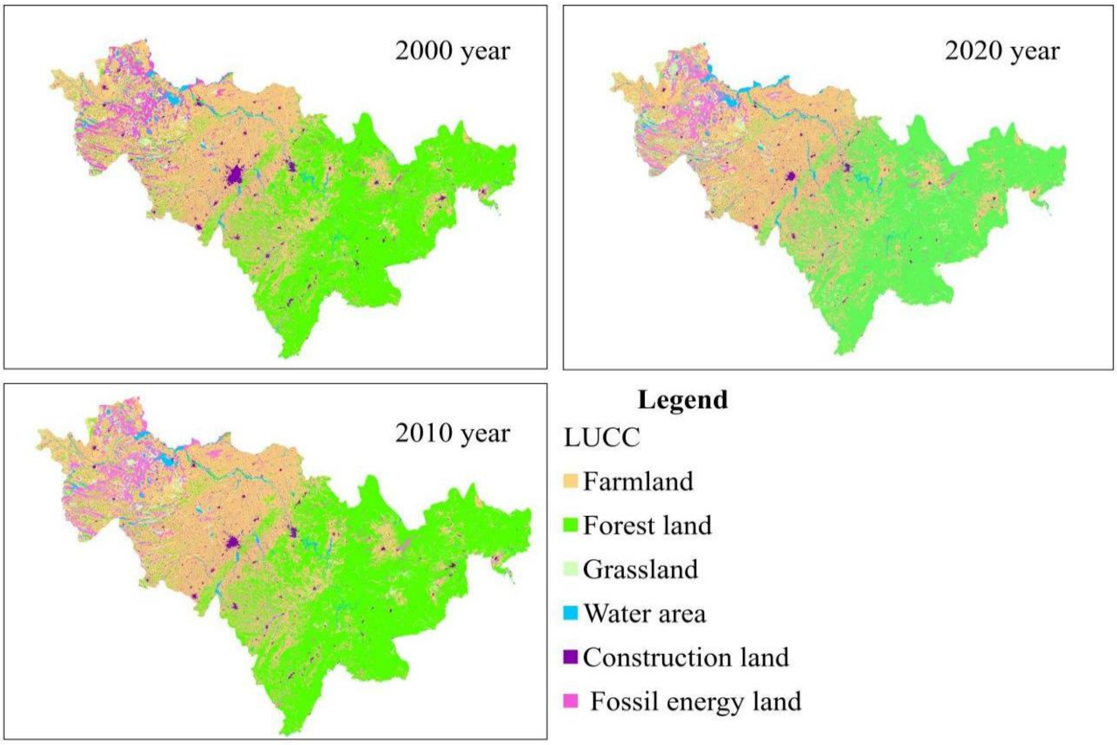

Figure 1. *Land use map of Jilin Province from 2000-2020*

Natural condition

Jilin Province is one of the six major forest areas in China, and is also located in the world-famous black land belt. The farmland area of the province is 7.03 million ha, accounting for about 37% of the total land area of the province, ranking the fifth in China. Compared with the whole country, the farmland area of Jilin Province accounts for about 4.4% of the national arable land area, and the basic farmland accounts for about 4.4% of the whole country. The average altitude of Songliao Plain is between 110 m and 200 m, and the fertile land in the plain is an important grain production base in China. The characteristics of rain and heat in the same season in Jilin Province are very beneficial to the growth of all kinds of crops.

Climate profile

Jilin Province is located in the middle latitude of the northern hemisphere, located in the east of the Eurasian continent. It is the northernmost part of the temperate region of

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China, touching the sub-cold zone. Jilin Province has a temperate continental monsoon climate, with dry spring, hot and rainy summer and cold winter. From southeast to northwest from the humid climate to semi-humid climate to semi-arid climate. The annual average temperature in most parts of the province is 3-5℃, the annual precipitation in the province is 550-910 mm, and the average temperature in winter is below-11℃. The average air temperature in the summer plains is above 23℃.

Hydrographic overview

The rivers of Jilin Province are divided into five river systems: Songhua River, Liaohe River, Yalu River, Tumen River and Suifenhe River. In winter, the river surface is frozen, in spring ice flow on river surface and while in summer more snowmelt water, posing damage to buildings along the river.

Wetland overview

Jilin Province is rich in wetland resources. According to the data of the “three adjustments” of land, the total area of wetlands in Jilin Province is 230,300 ha, and the total amount of resources is relatively rich, playing an irreplaceable role in regulating climate and maintaining ecosystem balance.

Study content and methods

Type and distribution of land use in Jilin Province

Different types of land in different spatial and geographical locations are affected by many factors such as natural geographical conditions and social and economic conditions.

Ecological footprint in Jilin Province

The calculation of the ecological footprint entails quantifying the consumption of natural resources and the waste generated by human activities to evaluate the impact of human society on the ecological environment. This process requires not only detailed data collection regarding resource usage but also a thorough analysis of the environmental burdens imposed by the by-products of these activities. Specifically, the calculation of the ecological footprint necessitates comprehensive documentation of the types and quantities of natural resources utilized in daily life across different regions. These include the arable land required for food production, forest areas involved in timber extraction, and fossil fuel reserves needed to meet energy demands. Additionally, this calculation must account for the by-products generated during resource utilization, such as the effects of carbon dioxide emissions on global climate change and the threats posed by urban solid waste to ecosystem health. Through this systematic and comprehensive quantification approach, ecological footprint research provides policymakers with critical insights into the sustainability of current development models and supports the formulation of more environmentally friendly strategies to mitigate pressures on the natural environment. Furthermore, this methodology enhances public awareness of environmental issues and underscores the significance of individual actions in maintaining global ecological balance. In summary, the calculation of the ecological footprint is both a vital area of scientific inquiry and an essential tool for steering societal development toward greater sustainability.

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Ecological carrying capacity

With the emergence of environmental destruction, irrational use of land resources, resource shortage and other problems, the relevant research on ecological carrying capacity has become a hot topic (Mao and Yu 2001). The assessment of ecological carrying capacity can understand whether the ecosystem is in a state of balance. If the intensity of human activities exceeds the maximum limit of ecological carrying capacity, it may lead to the imbalance of the ecosystem and cause environmental problems. Assessing ecological carrying capacity helps to formulate reasonable environmental protection objectives and targeted protection measures, thereby reducing the negative impact of human activities on the ecosystem and maintain the ecological balance.

Ecological deficit/surplus

When the ecological carrying capacity of a region is lower than its ecological footprint, an ecological deficit arises. The magnitude of this deficit corresponds to the difference between the ecological carrying capacity and the ecological footprint. An ecological deficit signifies that the human demand in the region surpasses its ecological supply. To sustain the current living standards of its population, the region may either import the necessary resources from external sources to balance its ecological footprint or deplete its natural capital to compensate for the shortfall in resource availability. Both approaches indicate that the regional development model is operating in a relatively unsustainable manner, with the extent of unsustainability quantified by the ecological deficit. Conversely, when the ecological carrying capacity exceeds the ecological footprint, an ecological surplus emerges. This surplus demonstrates that the region’s ecological capacity is sufficient to meet human demands, and the inflow of natural capital exceeds consumption requirements. As a result, the total stock of natural capital in the region may increase, potentially enhancing its ecological resilience and capacity over time. Such a scenario reflects a relatively sustainable consumption pattern. An ecological deficit reveals that, given the prevailing technological advancements and consumption patterns, the region’s demand for natural resources outstrips the ability of its ecosystem to provide the necessary resources and services, thereby leading to resource overexploitation and environmental degradation. Persistent ecological deficits can undermine the long-term sustainability of ecosystems and may precipitate resource scarcity and environmental crises. Therefore, ecological deficits and surpluses serve as critical indicators for assessing the sustainability of regional development.

Per capita ecological footprint

The per capita ecological footprint can show the number of natural resources consumed by residents in Jilin Province. The higher the per capita ecological footprint value, the more natural resources consumed by individuals, and the more natural resources wasted and consumed. Conversely, the lower per capita ecological value indicates that the pressure of the ecosystem is less, which is more conducive to the sustainable development of the ecosystem.

Ecological sustainable development

Ecological sustainable development is a concept with profound implications. At its core, it emphasizes fulfilling the needs of the present generation without diminishing the capacity

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of future generations to meet their own requirements. This approach not only prioritizes the efficient use and conservation of natural resources but also underscores the importance of fostering coordinated development and harmonious integration among ecological, economic, and social systems. Through this holistic framework, ecological sustainable development aims to preserve the structural integrity, functional stability, and regenerative capabilities of ecosystems. Furthermore, it addresses the balance between social equity and economic growth by advocating for the transformation of economic models toward low-carbon and circular systems through technological innovation and green transitions.

Land use types and related ecological footprint calculations

Data source

The land cover data

The land cover data used in this study is derived from the annual 30-m resolution land cover dataset of China released by the team of Professors Yang Jie and Huang Xin from Wuhan University. The dataset covers the period from 1990 to 2020. It was compiled by the research team led by Professors Yang Jie and Huang Xin and officially released in 2021 (Yang and Huang, 2021). The high-resolution feature of this dataset enables it to accurately reflect the land cover changes over a long time series, providing crucial basic data support for regional environmental change analysis, urban expansion monitoring, and ecosystem dynamics research. Moreover, the wide applicability of this dataset has been verified in multiple fields, including climate change research, land use planning, and natural resource management. By using this dataset, the accuracy and scientific nature of the data analysis in this study are ensured.

The NPP data

The NPP data were obtained from the MODIS sensor available on NASA’s official website, specifically for the years 2000-2010 and 2010-2020. This study conducts a comparative analysis of the data from these two periods.

Factors of production and national ecological footprint

Production factor and national ecological foot print data from the global footprint network, the production factor aspect of this data focuses on the efficiency with which nations use their resources in agricultural, forestry, fishing, and other productive sectors. This study takes the production factors of China in 2000, 2010 and 2020 as those of Jilin Province in the same years, and conducts a comparative analysis of the ecological footprint, ecological deficit/surplus between China and Jilin Province.

The ecological footprint data

The ecological footprint data is derived from the Jilin Statistical Yearbook and the FAO website for 2001-2011 and 2011-2021. Compare two ten years over a time period.

Data processing balancing factors

The NPP data and LUCC data were subjected to cutting, recalculation, resampling, and other preliminary processing steps. These processed datasets were then integrated,

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and through subsequent calculations, the balancing factors for each land use type were successfully obtained.

Ecological footprint

By conducting descriptive statistical analysis and processing of the data obtained from the "Jilin Statistical Yearbook" and the Food and Agriculture Organization of the United Nations (FAO), the ecological footprints associated with various land types were quantified. Subsequently, the resulting data were presented in a visual format to enhance interpretability (*Table 1*).

Current situation of land use

Dynamic attitude of land use

Under the influence of natural and human factors, the variation amplitude and speed of various land use types in different time periods are different, and there are spatial differences (*Table 2*). The speed of land use change can be measured by the dynamic model of land use type, which can not only represent the time series variation of a single land use type, but also analyze the overall status of regional land use dynamics and its regional differentiation. We quote the following model for analysis:

$$K = \frac{Ua - Ub}{Ua} * \frac{1}{T} * 100\% \qquad \text{(Eq.1)}$$

Equation 1, K is the attitude of a land use type during the study period; Ua, Ub are the number of a land use type at the beginning and end of the study period; T is the length of the study period.

Change rate of land use

The degree of change of land use types in the spatial location and range in a certain time is usually quantified by the area change within a specific time period, and is used to measure the spatial variation of land use types on a certain time scale.

$$L = \frac{Ua - Ub}{Ua} * 100\% \qquad \text{(Eq.2)}$$

In *Equation 2*, L is the change rate of land use; Ua and Ub are the number of certain land use types at the beginning and end of the study period respectively.

Land use transfer matrix

The land use transition matrix is a specific application of the Markov model in the study of land use change, providing a quantitative method to describe the transformation relationship between different land types. In this matrix, the columns represent the land types at the initial time point (T1), and the rows represent the land types at the end time point (T2). Each matrix element represents the area or area ratio of the transformation from one land type to another, thereby reflecting the change characteristics of land use types in the region from the initial to the final period and the process of their mutual conversion.

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Ecological footprint model

Table 1. *Classification of ecological footprint items*

Classification of ecological footprint projects										
Farmland	Grain	Vegetables	Tubers	Beans	Oil	Tea	Pork	Beans	Milk	Eggs
Forest land	Fruit	Dry fruit	Rubber							
Grassland	Beef	Mutton								
Water area	Aquatic product									
Construction land	Electric power									
Fossil energy land	Natural gas	Oil	Coal products							

Ecological footprint computational model

The calculation of land ecological footprint can show the impact of various human activities on resource consumption and environment. The area of ecologically productive land necessary to maintain the sustainable survival of the population at a certain level of material consumption, and the factors affecting the ecological footprint include population size, consumption, resource status, etc. (Wang, 2018).

$$EF = N * \mathrm{ef} = \mathrm{N} * \left(\frac{\mathrm{n_i}}{\mathrm{g_i}}\right) \quad \text{(Eq.3)}$$

In *Equation 3*, EF: represents the ecological footprint of total biological resources in the region; N: indicates the total population of the region. ef: per capita ecological footprint; i: represents the ecological footprint of a project, n_i: represents the consumption of a biological resource project for a certain land type in the region, and g_i: represents the average productivity increase of the project worldwide.

The ecological footprint of energy resources is calculated using the energy calculation formula of energy classification (Zhang et al., 2025):

$$EEF = (EC * ESCC * ef * eq)/(WAF * TP) \quad \text{(Eq.4)}$$

In *Equation 4*, EEF: energy footprint; EC: single energy type consumption in the region; ESCC: this standard coal coefficient; ef: standard coal conversion coefficient (29.3076GJ/tce); eq: equivalent coefficient (fossil energy land: 1.28); WAF: global average energy ecological footprint; TP: total number of people in the region.

Ecological carrying capacity model

Ecological carrying capacity is based on a stable ecosystem, the resources and products supplied to society in a certain area are converted into the sum of all biologically productive land area (Lv et al., 2014). The ecological environment and resources of different countries and regions are unequal, so the production capacity of different regions cannot be compared with each other. Therefore, in order to eliminate such differences, Wackernagel et al. (1999) introduced the concepts of balancing factor and yield factor, so as to transform the national average biological production (Wackernagel et al. (1999; Han, 2018). The equilibrium factor is derived by comparing the average ecological productivity of land area with the global ecological productivity of land. The yield factor

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is measured by the ratio of crop yield in the region to the global average crop yield or the ratio of the yield of a single crop in the region to the global average crop yield (*Table 3*).

Table 2. *Data on the ecological footprint of fossil energy land*

	Coal	Hard coke	Gasoline	Diesel oil	Fuel oil	Electric power	Natural gas
Reduced standard coal coefficient (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, China National Standardization Administration, 2020) (kgce/kg)	0.71	0.97	1.47	1.46	1.43	0.35	1.33
Global average energy ecological footprint (Costanza and Daly, 1992) ($GJ \cdot hm^{-2}$)	55	55	93	93	71	1000	93

Table 3. *In 2000-2020 yield factor*

Year \ Balancing factor	Farmland	Forest land	Grassland	Water area	Construction land
2000	1.77	1.83	0.22	0.17	1.77
2010	1.09	1.50	0.34	0.27	1.09
2020	1.65	1.69	0.35	0.32	1.65

$$EC = N * ec = \mathrm{N} * \sum a_j * b * y_i \qquad \text{(Eq.5)}$$

In *Equation 5*, EC: represents the ecological carrying capacity; N: the total population of the region; ec: the per capita ecological carrying capacity; a_j: the per capita ecological productive land area of the region; b: the balancing factor; y_j: the yield factor.

Ecological deficit/surplus model

This model is mainly an indicator to describe the ecological environment in the study area, which is calculated by ecological footprint and ecological carrying capacity.

If the value is positive, it indicates that the ecological resource demand of the region is large, and the ecological environment cannot bear the demand, showing a deficit state. Similarly, if it is negative, it means that the ecological resource demand of the region is in surplus within the range of ecological carrying capacity.

$$ED(ES) = EC - EF \qquad \text{(Eq.6)}$$

In *Equation 6*, ED: represents ecological deficit; ES: ecological surplus; EF: total ecological *footprint; ECC: Ecological carrying capacity.*

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Ecological sustainability assessment model

The sustainability of Jilin ecosystem was assessed based on the ecological footprint model.

$$e_g = \frac{ef * N}{GDP} \quad \text{(Eq.7)}$$

In *Equation 7*, e_g: ecological footprint of 10,000 yuan GDP; ef: per capita ecological footprint; N: Total population.

$$EE = \frac{GDP}{EF} * 100\% \quad \text{(Eq.8)}$$

In *Equation 8*, EE: ecological footprint utilization efficiency; EF: Ecological footprint.

$$E_{SI} = \frac{EC}{EC + EF} \quad \text{(Eq.9)}$$

In *Equation 9*, E_{SI}: ecosystem sustainability index; EF: Ecological footprint; EC: Ecological capacity (*Table 4*).

***Table 4.** Balancing factor for 2000-2020*

Year \ yield factor	Farmland	Forest land	Grassland	Water area	Construction land
2000	1.31	1.18	0.81	1.13	2.19
2010	1.32	1.18	0.81	1.13	2.19
2020	1.35	1.18	0.81	1.13	2.24

Analysis of present situation of land use in Jilin Province

Figure 1 shows the status of land use in 2000, 2010 and 2020. It can be seen that in western Jilin, farmland occupies a larger area, while in eastern Jilin, forest land occupies a larger area, and most of the unused land is also distributed in western Jilin. From 2000 to 20 years, the area of building land has been continued to increase significantly, while the area of grassland has decreased significantly.

Table 5 shows the area of land use types in 2000 to 2020. It can be seen that in 20 years, the area of farmland has been increasing continuously, the area of forest land has shown a trend of first increasing and then decreasing, while the area of grassland has shown a trend of substantial decrease, the area of water area has shown a trend of first decreasing and then increasing, and the area of construction land has been continuously increasing. The area of unused land increases first and then decreases.

Tables 6 and *7* show the dynamic changes, changing value and change rate of land use during 2000-2010 and 2010-2020. Between 2000 and 2010, the area of farmland increased by 282.62 km^2, the area of forest land increased by 61.08 km^2, while the area of grassland and water area decreased by 857.99 and 637.92 km^2, and the land for construction and unused land increased by 603.05 and 551.41 km^2, respectively. From 2010 to 2020, the area of

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farmland will increase by 823.19 km^2, while the forest land, grassland and unused land will decrease by 696.22, 378.65 and 771.01 km^2, respectively, while the water area and construction land will increase. Increased by 143.99 and 866.55 km^2, respectively.

Table 5. *Area of land use type in Jilin Province from 2000-2020*

Year \ Land use area (km^2)	Farmland	Forest land	Grassland	Water area	Construction land	Unused land
2000	75394.26	84045.06	8318.19	4751.13	6578.84	11603.52
2010	75676.88	84106.15	7460.20	4113.21	7181.90	12154.93
2020	76500.06	83409.92	7081.55	4257.20	8048.44	11383.92

Table 6. *Dynamic attitude, change value and change rate of land use area in Jilin Province from 2000-2010*

2000-2010	Farmland	Forest land	Grassland	Water area	Construction land	Unused land
Dynamic attitude	0.04%	0.01%	-1.15%	-1.55%	0.84%	0.45%
Changing value (km^2)	283.62	61.08	-857.99	-637.92	603.05	551.41
Rate of change	0.37%	0.07%	-11.50%	-15.51%	8.40%	4.54%

Table 7. *Dynamics, changes, and rates of land use area in Jilin Province from 2010-2020*

2010-2020	Farmland	Forest land	Grassland	Water area	Construction land	Unused land
Dynamic attitude	0.11%	-0.08%	-0.53%	0.34%	1.08%	-0.68%
Changing value (km^2)	823.19	-696.22	-378.65	143.99	866.55	-770.01
Rate of change	1.08%	-0.83%	-5.35%	3.38%	10.77%	-6.77%

From the land use transition matrix presented in *Table 8* for the period from 2000 to 2020, it is evident that during this timeframe, 5950 km^2 of forest land were converted into farmland, representing the largest transformation among all land use types. Additionally, 1753 km^2 of grassland and 1844 km^2 of construction land were also transformed into farmland, with the conversion areas of these two land use types being relatively similar. Furthermore, 1203 km^2 of unused land were converted into farmland, whereas the area of water bodies converted into farmland was the smallest, amounting to only 644 km^2; A total of 5004 km^2 of farmland was transformed into forest land, while 1429 km^2 of grassland underwent conversion to forest land. The smallest area of transformation occurred in construction land, with only 147 km^2 being converted into forest land. Additionally, 234 km^2 of water areas and 445 km^2 of unused land were also converted into forest land. Among all land use types, farmland 979 km^2 and forest land 1013 km^2 exhibited the most significant conversions to grassland. Construction land contributed minimally to this transition, with only 41 km^2 being converted to grassland. Water areas 104 km^2 and unused land 860 km^2 also underwent notable transformations into grassland. Farmland demonstrated the largest conversion to water areas, with 662 km^2 undergoing this change. Grassland 56 km^2 and construction land 28 km^2 showed minimal transitions to water areas, whereas forest land 311 km^2 and unused land 252 km^2 exhibited moderate conversions. A substantial portion of farmland 3086 km^2 was converted into construction

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land, followed by forest land 237 km^2 and unused land 120 km^2, which displayed similar conversion patterns. Grassland 80 km^2 and water areas 43 km^2 exhibited limited transitions to construction land. Farmland 553 km^2 and forest land 377 km^2 underwent notable conversions to unused land. Grassland 914 km^2 and water areas 778 km^2 demonstrated significant transformations into unused land, whereas construction land contributed minimally to this transition, with only 37 km^2 being converted.

Table 8. *Land use transfer matrix of Jilin Province from 2000-2020*

2000 \ 2020	Farmland	Forest land	Grassland	Water area	Construction land	Unused land
Farmland	65098.27	5004.26	979.14	662.54	3086.60	553.47
Forest land	5950.45	76141.90	1013.23	311.40	237.95	377.88
Grassland	1753.74	1429.12	4081.68	56.11	80.57	914.67
Water area	644.59	234.27	104.18	2942.33	13.08	778.63
Construction land	1844.33	147.14	41.16	28.81	4479.83	37.25
Unused land	1203.32	445.16	860.84	252.23	120.03	8720.51

Figure 2 displays a chord diagram representing the land use transition matrix. In this diagram, the chords linking various sectors illustrate the relationships or transitions between different categories. By examining the color variations of the distinct land types depicted, one can easily grasp the conversion dynamics and areas involved in these transitions. Specifically, the total area for farmland is 75,384 km^2, forest land spans 84,032 km^2, grassland covers 8315 km^2, water bodies encompass 4747 km^2, construction land totals 6578 km^2, and unused land amounts to 11,602 km^2. The chord colors predominantly align with the main node's color, highlighting land types with significant conversion areas. From this, it is evident that in the transition between farmland and forest land, more farmland has been converted to forest land compared to the reverse process. Similarly, in the case of forest and grassland transitions, the shift from forest to grassland is more extensive than the conversion from grassland to forest.

Figure 3 shows the changing trend of net primary productivity (NPP) in Jilin Province from 2000 to 2020. As an important indicator for measuring the productivity of ecosystems and the efficiency of energy conversion, NPP can directly reflect the production capacity and energy utilization efficiency of ecosystems. It can be observed from the figure that during these 20 years, the NPP in Jilin Province has generally shown a continuous upward trend. Specifically, the NPP in different regions of Jilin Province shows significant spatial differences. The NPP in the western region is relatively low, which may be related to the relatively dry climate conditions, less precipitation and lower soil fertility in this area. In contrast, the NPP in the eastern region is relatively high, benefiting from its humid climate conditions, abundant precipitation and higher vegetation coverage. These natural conditions provide a more favorable environment for plant growth in the eastern region, thereby enhancing the productivity and energy conversion efficiency of the ecosystem. In addition, in this study, the NPP data was further applied to the calculation and analysis of the balancing factor. The balancing factor is one of the important parameters for evaluating the stability and sustainable development capacity of ecosystems. By combining NPP data, the ecological differences between different regions can be quantified more accurately, and it can provide a basis for formulating scientific and reasonable ecological protection and management strategies.

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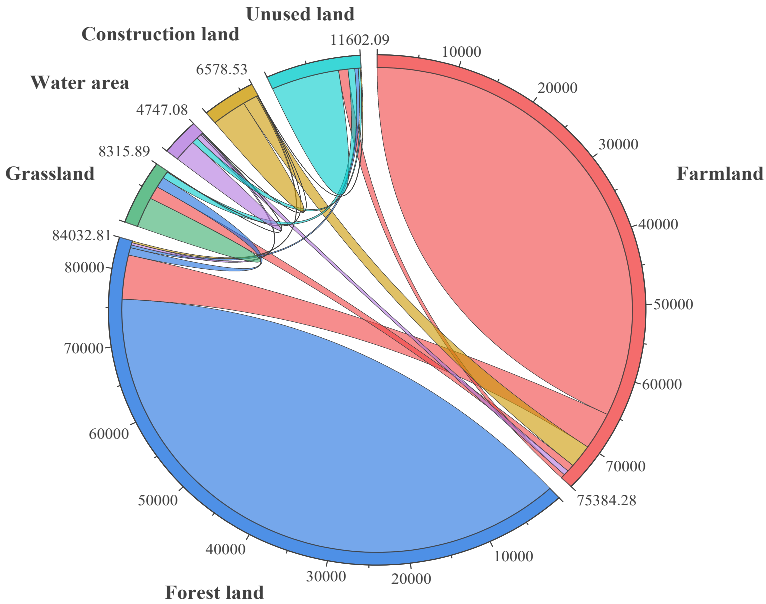

***Figure 2.** String diagram of land use transfer matrix from 2000-2020*

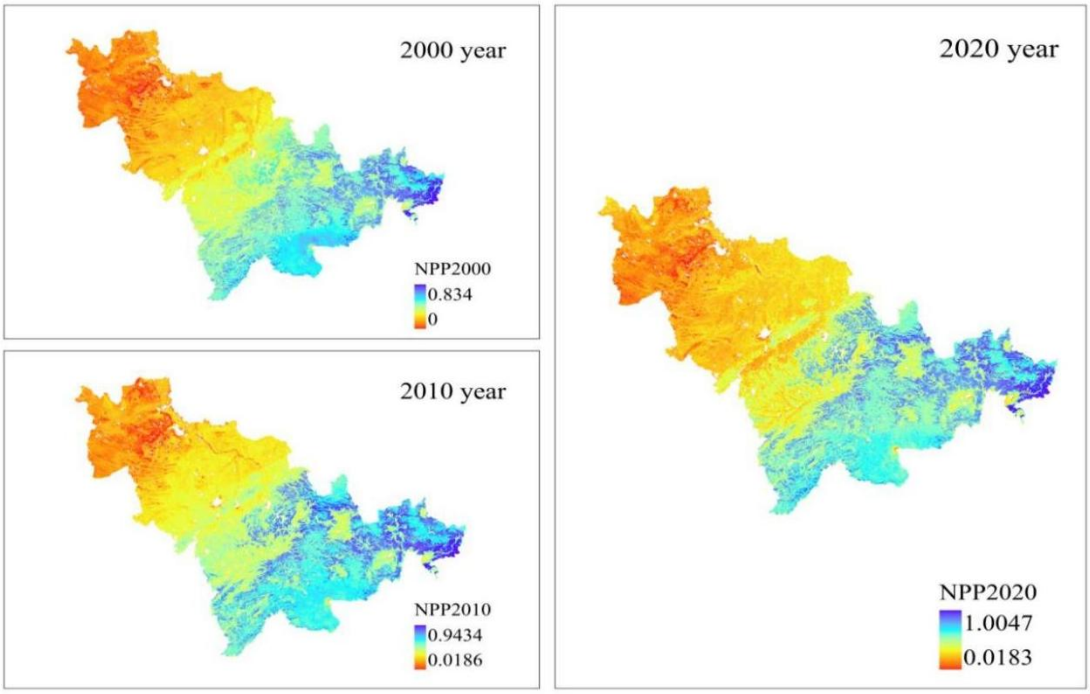

***Figure 3.** Schematic representation of NPP variations in Jilin Province from 2000 to 2020*

Ecological footprint analysis of wetlands in Jilin Province

Ecological footprint calculation and analysis

From *Table 9*, it can be observed that the ecological footprint of farmland increased by 0.536 gha over the 20-year period, representing a growth rate of 0.38%. The ecological footprint of forest land showed a trend of first decreasing and then increasing. In 2020, the ecological footprint was roughly the same as that in 2000, while in 2010, it dropped

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from 0.252 gha in 2000 to 0.118 gha, a reduction of 0.134 gha, or 53%. The ecological footprint of grassland exhibited a pattern of first increasing and then decreasing. The ecological footprint in 2020 was basically the same as that in 2000, but in 2010, it was relatively high, increasing by 0.019 gha compared to 2000 (from 0.066 gha to 0.085 gha), a growth rate of 29%. The ecological footprint of water areas showed a continuous growth trend, increasing by 0.007 gha from 2000 to 2020, with a growth rate of 0.39%. The ecological footprint of construction land showed a trend of first increasing and then decreasing. The ecological footprint in 2020 was the same as that in 2000, while in 2010, it increased by 0.0004 gha compared to 2000. The ecological footprint of fossil energy land showed significant differences among 2000, 2010, and 2020, with the ecological footprint in 2020 being 0.054 gha less than that in 2010. *Table 10* presents the ecological footprint data of each land type from 2000 to 2020, which was calculated by multiplying the per capita ecological footprint by the total population of Jilin Province. The trend of change is consistent with that of the per capita ecological footprint.

Table 9. *Ecological footprint per capita by land type in Jilin Province from 2000-2020*

	Farmland	Forest land	Grassland	Water area	Construction land	Fossil energy land
2020	1.400	0.258	0.068	0.019	0.005	1.439
2010	1.135	0.118	0.085	0.013	0.009	1.493
2000	0.864	0.252	0.066	0.012	0.005	0.506

Table 10. *Ecological Footprint by Land Type in Jilin Province, 2000-2020*

	Farmland	Forest land	Grassland	Water area	Construction land	Fossil energy land
2020	33582218.72	6189691.21	1630944.53	466838.38	119972.00	34537519.55
2010	31165125.32	3231515.63	2329316.32	343531.49	247194.00	41005756.03
2000	23181823.66	6756213.37	1771015.78	318202.07	134085.00	13564930.64

Figure 4 shows the distribution of per capita ecological footprints of various land use types from 2000 to 2020. The analysis indicates that the ecological footprint of farmland has shown the most significant growth trend over these 20 years. The ecological footprints of fossil energy land and forest land also demonstrated a clear upward trend from 2000 to 2010. However, by 2020, the ecological footprint of fossil energy land had slightly declined, while the growth trend of forest land gradually flattened. Additionally, the ecological footprints of water areas, construction land, and grassland did not undergo significant changes from 2000 to 2020.

Through the analysis of *Table 11*, it can be found that the overall ecological carrying capacity shows a trend of first decreasing and then increasing, with the ecological carrying capacity reaching its maximum in 2020. Among the various years, the ecological carrying capacity of farmland has the highest proportion, followed by forest land and construction land, while the proportions of grassland and water areas are relatively low. Specifically, the per capita ecological carrying capacity of farmland decreased by 0.370 gha at first and then increased by 0.347 gha during the research period; forest land also showed a trend of first decreasing and then increasing, with a decrease of 0.082 gha and an increase of 0.209 gha

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respectively; grassland and water areas demonstrated a continuous decreasing trend, with a decrease of 0.004 gha and 0.003 gha respectively; the ecological carrying capacity of construction land also showed a trend of first decreasing and then increasing, with a decrease of 0.029 gha and an increase of 0.068 gha respectively.

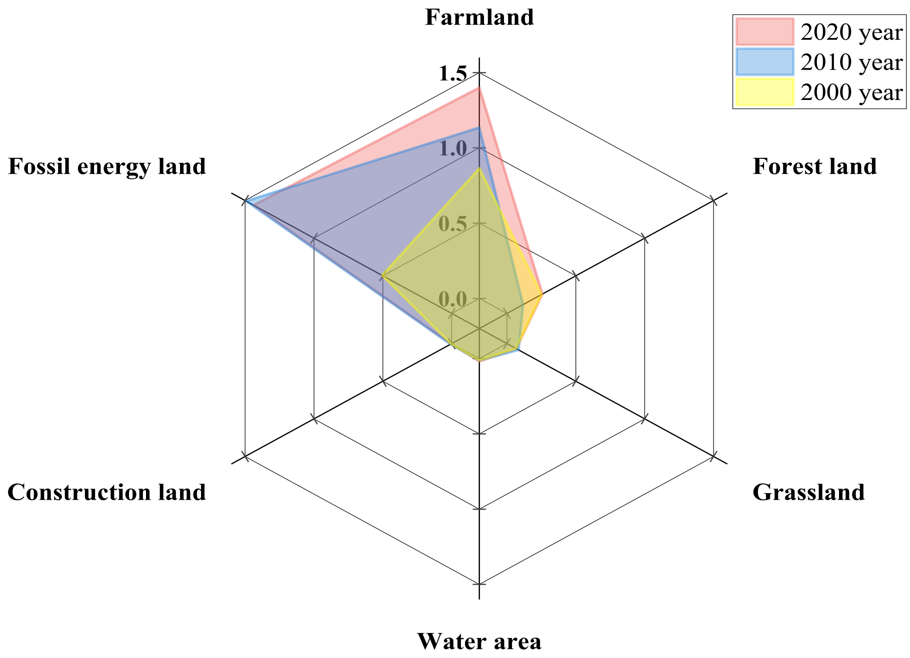

Figure 4. *Radar chart of per capita ecological footprint for various land use types*

Table 11. *Per capita ecological carrying capacity (gha) from 2000-2020*

	Farmland	Forest land	Grassland	Water area	Construction land	Total ecological carrying capacity
2020	0.744	0.752	0.005	0.003	0.130	1.635
2010	0.397	0.543	0.008	0.005	0.062	1.014
2000	0.627	0.625	0.009	0.006	0.091	1.357

The data in *Table 12* shows that in 2000, Jilin Province's ecological resources were in a surplus state, indicating that the natural resources supply at that time could meet the demands of human activities. However, starting from 2010, this situation changed significantly, with ecological resources turning into a deficit state, clearly reflecting that the local ecological resources could no longer fully meet the demands of human activities for resources, and human production activities also exert a huge pressure on the ecosystem. By 2020, the ecological deficit problem had further intensified, with the growth rate compared to the base year reaching 0.653. This trend not only reveals the changes in the supply and demand relationship of ecological resources in Jilin Province but also highlights the potential pressure that long-term resource utilization patterns may bring.

Figures 5 and *6* respectively present the comparison of ecological deficits (surpluses) between the whole country and Jilin Province as well as the comparison of per capita ecological footprints. The analysis indicates that the level of ecological deficits

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(surpluses) in Jilin Province is higher than the national average. Additionally, in 2020, the per capita ecological footprint of Jilin Province was lower than the national average, while in 2000, the per capita ecological footprints of Jilin Province and the whole country were relatively close.

Table 12. *Ecological deficit (surplus), 2000-2020*

	Farmland	Forest land	Grassland	Water area	Construction land	Total ecological deficit (surplus)
2020	-0.656	-0.250	-0.068	-0.019	-0.004	-0.997
2010	-0.738	0.426	-0.077	-0.008	0.053	-0.344
2000	-0.238	0.373	-0.057	0.006	0.086	0.170

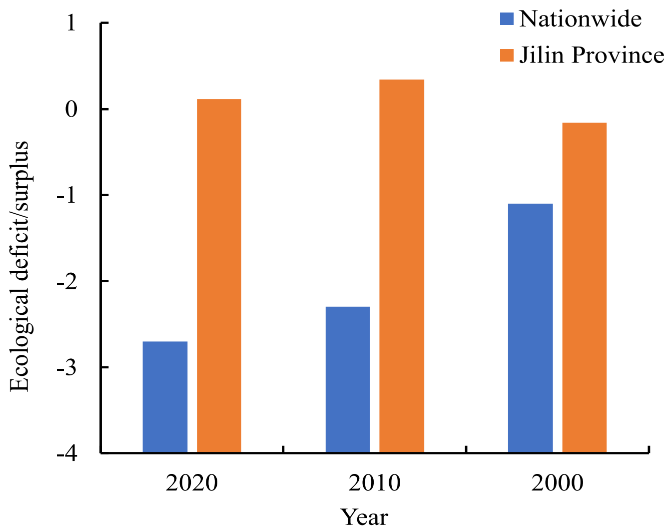

Figure 5. *Comparison of National and Jilin Province's Ecological Deficit (Surplus) from 2000-2020*

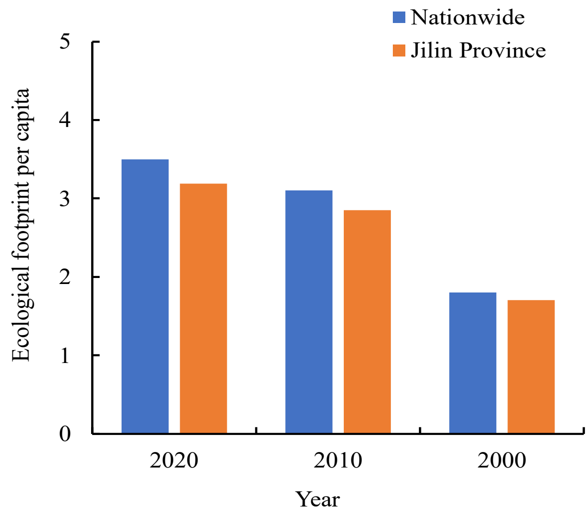

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***Figure 6.** Comparison of per capita ecological footprint of China and Jilin Province from 2000-2020*

Assessment of the sustainability of ecosystems

According to the data analysis in *Table 13,* the ecological footprint per 10,000 yuan of GDP reflects the changing trend of resource utilization efficiency in Jilin Province. From 2000 to 2010, this indicator decreased by 1.389/hm², and further declined to 1.989/hm² by 2020. The ecological footprint utilization efficiency, as an important indicator for measuring resource utilization efficiency and sustainability, shows a trend of increasing first and then decreasing. Specifically, it increased by 0.435% from 2000 to 2010, but decreased by 0.802% from 2010 to 2020. Additionally, the sustainable index of the ecological footprint is a key indicator system for comprehensively assessing the level of regional sustainable development. The data shows that the sustainable index of Jilin Province first decreased and then increased, but the sustainable index in 2020 was still lower than that in 2000. The specific changes were: a decrease of 0.104 from 2000 to 2010, and an increase of 0.056 from 2010 to 2020. Based on the classification standard of the degree of ecosystem sustainable development (Zhang et al., 2024) (strongly sustainable: $ESI \geq 0.80$; moderately sustainable: $0.65 \leq ESI < 0.80$; weakly sustainable: $0.50 \leq ESI < 0.65$; weakly unsustainable: $0.25 \leq ESI < 0.50$; moderately unsustainable: $0.10 \leq ESI < 0.25$; strongly unsustainable: $0 < ESI < 0.10$), it can be concluded that Jilin Province was in a weakly sustainable state in 2000, but in a weakly unsustainable state in 2010 and 2020 (*Figure 7*).

***Table 13.** Ecological footprint, ecological footprint utilization efficiency, and sustainability index per 10,000 yuan of GDP from 2000-2020*

	Ecological footprint of 10,000 yuan of GDP/hm^2	Ecological footprint utilization efficiency (%)	Sustainability index
2020	0.622	1.609	0.483
2010	1.222	0.818	0.427
2000	2.611	0.383	0.531

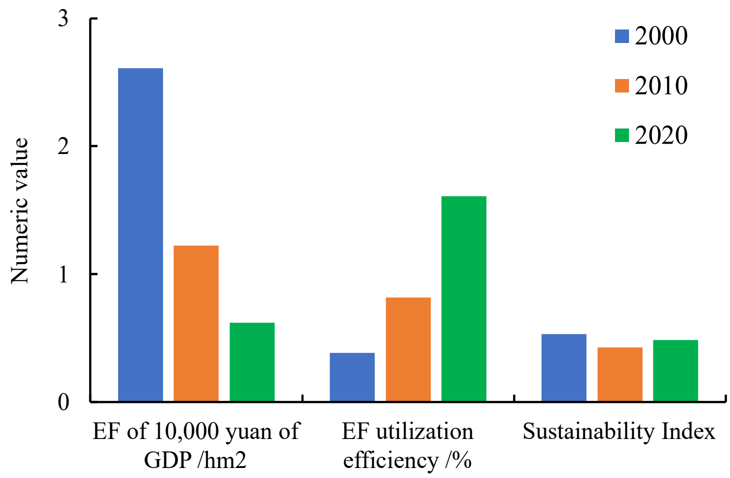

***Figure 7.** Bar chart of ecological sustainable*

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Figure 6 presents a bar chart of the ecological sustainable development assessment, from which the changing trend of ecological sustainable development in Jilin Province can be clearly observed. Specifically, the ecological footprint per 10,000 yuan of GDP has significantly decreased from 2000 to 2020, indicating an effective improvement in resource utilization efficiency; the ecological footprint utilization efficiency has greatly increased over these 20 years, further reflecting the optimization effect of resource utilization. However, the sustainable development index has not shown a distinct fluctuation trend during this period and has remained relatively stable overall.

Conclusions and prospects

Summary of study conclusions

In 2000, 2010 and 2020, the per capita ecological footprint of Jilin Province generally showed an increasing trend, rising from 1.705 gha in 2000 to 3.189 gha in 2020. The main driving factors for this change include population growth, increased resource demand, accelerated urbanization and the improvement of economic development level. Meanwhile, the per capita ecological carrying capacity of Jilin Province showed a trend of first decreasing and then increasing: it decreased by 0.343 gha from 1.357 gha to 1.014 gha between 2000 and 2010, and then increased by 0.621 gha from 1.014 gha to 1.635 gha between 2010 and 2020. Combining the changing trend of Jilin Province's population (first increasing and then decreasing) and the current situation of land use, it can be known that between 2000 and 2010, due to rapid population growth, rapid economic development and excessive land reclamation, the ecological carrying capacity decreased; while between 2010 and 2020, thanks to policy support and the increase in productive land area, the ecological carrying capacity of Jilin Province gradually recovered. The ecological deficit (surplus) reflects the extent to which the ecological environment and resources in Jilin Province can meet the demands of human activities. In 2000, the value was positive, indicating that the ecological resources at that time could fully meet the demands of human activities; however, by 2010, the value had dropped to -0.344 gha, and further declined to -0.997 gha by 2020. This indicates that the ecological pressure in Jilin Province has been continuously increasing, and the ecological resources can no longer fully meet the demands of human activities. In terms of the sustainable development of ecological resources in Jilin Province, the ecological footprint per 10,000 yuan of GDP in Jilin Province showed a downward trend from 2000 to 2020. A lower ecological footprint per 10,000 yuan of GDP indicates a higher efficiency in the utilization of ecological resources within the region, which is conducive to promoting the sustainable development of the ecosystem. Additionally, the efficiency of ecological footprint utilization in Jilin Province has been on the rise. A higher value of ecological footprint utilization efficiency means that each unit of ecological resources can create greater economic value, thereby reflecting an improvement in resource utilization efficiency. Meanwhile, the sustainability index is an important indicator for assessing the level of sustainable development in Jilin Province. Data shows that the sustainability index of Jilin Province was in a weakly sustainable state in 2000, dropped to 0.427 in 2010, entering a weakly unsustainable stage, and although it increased to 0.483 in 2020, it still remained within the weakly unsustainable range.

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Analysis of existing problems and deficiencies

This study is based on the traditional ecological footprint model for analysis. This model is a two-dimensional model for productive land, with its core being the exclusive assumption of land functions. However, this assumption to some extent limits the ability to comprehensively measure the non-productive products of the ecosystem. The calculation of ecological footprint requires a large amount of data support, covering aspects such as land use, population size, and consumption of productive products. Due to the complexity of data acquisition and processing, it is difficult to fully guarantee the accuracy and completeness of the data. In addition, this study mainly conducts calculations and analyses based on existing data, which can visually interpret the current state or the state that has occurred, but has limitations in making precise predictions about future trends (Hou et al., 2019). It is worth noting that most research on the ecological footprint model originates from abroad, and domestic scholars' innovative research and development in this field is still insufficient and needs to be further strengthened.

Future and prospects

The multi-sequence study of ecological footprint can more clearly reveal the expanding trend of ecological deficit from the time dimension, thereby deepening the public's understanding of ecological environment protection and sustainable development. Meanwhile, the ecological footprint analysis based on spatial span helps to assess the ecological pressure and sustainable development level among different regions, providing a scientific basis for regional planning and policy-making. In the future, the focus of ecological footprint research will be concentrated on the further precise application and modification of models, cross-temporal series analysis, spatial scale assessment, and innovative technology research and development, etc., to promote the coordinated sustainability of ecological environment protection and economic development.

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