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Natural capital accounting of cultivated land based on three-dimensional ecological footprint model-- A case study of the Beijing-Tianjin-Hebei region

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The fairness of the utilization of cultivated land resources is essential for the balanced development of the region, but there are few researches to analyze it. Against the background of the urgent need for farmland protection and ecological compensation, this paper takes cultivated land as the research object and uses a three-dimensional ecological footprint model to account for and analyze the utilization of natural capital stock and flow of cultivated land in Beijing-Tianjin-Hebei region from 2009 to 2016 in terms of footprint breadth and depth, so as to provide reference for cultivated land protection, ecological compensation and even coordinated regional ecological-economic development. The results show that from 2009 to 2016, the ecological footprint breadth of cultivated land in Beijing-Tianjin-Hebei region was generally low and the footprint depth was generally high, and the ecological footprint depth of cultivated land in the region as a whole tended to increase, except for Zhangjiakou and Chengde, which were able to achieve self-sufficiency in flow capital, 85% of the cities showed the phenomenon of depletion of cultivated land flow capital and intensification of stock capital depletion. After 2010, the overall Gini coefficient of the ecological footprint of cultivated land in the Beijing-Tianjin-Hebei area was less than 0.4, and the use of natural capital from cultivated land was relatively balanced. The study concludes that under the strategic role of Beijing-Tianjin-Hebei integration and collaborative development, the equity of natural capital utilization of cultivated land in each city in the Beijing-Tianjin-Hebei region has been improved, but the level of creating and utilizing natural capital flows of cultivated land still needs to be improved, and ecological protection of cultivated land needs to be further strengthened; the excessive depletion of natural capital of cultivated land caused by agricultural production can be used as a reference basis for cross-regional ecological compensation of cultivated land, thus supporting the ecological value of cultivated land. Over-consumption of natural capital from agricultural land caused by agricultural production can be used as a baseline for interregional ecological compensation of agricultural land, thus supporting the realization of the ecological value of agricultural land.

KEYWORDS

cultivated land resources, natural capital accounting, three-dimensional ecological footprint, ecological compensation, Beijing-Tianjin-Hebei region

1 Introduction

With the increasing development of social economy and rapid urban expansion, the problems of resource consumption, environmental pollution and ecological damage have become more and more prominent, and how to establish a sustainable human-land relationship and green economic development model has become a common concern of academia and society. (Chiritescu et al., 2013; Yang J. et al., 2019; Ouyang et al., 2020; Wang et al., 2020; Shmelev and Brook, 2021; Yang et al., 2021; Wang S. et al., 2022; Wang S. H. et al., 2022). As a key concept to measure sustainable development, natural capital has gradually attracted the attention of scholars (Fang, 2015; Yang and Hu, 2018; Fisher et al., 2021; Wu et al., 2021). Natural capital, refers to the stock of natural resources and environmental assets that can provide useful products or services in the present or the future, including cultivated land, forest, water, wetland and other ecosystems, ecological diversity and ecosystem services (Daly Herman, 1996; Costanza et al., 1997). The stability of regional natural capital stock is an important criterion for evaluating the sustainable development of a region, and the stock of natural capital in a region plays a fundamental role in supporting the life of the people and economic development of that place.

As an important component of natural capital, cultivated land is closely related to food security, social stability and ecosystem balance. Its utilization level is an important basis for formulating regional development strategy and planning. In December 2020, President Xi Jinping emphasized at the Central Rural Work Conference that "we should strictly guard the red line of 1.8 billion mu of cultivated land, take long and hard measures to implement the strictest cultivated land protection system", which has put forward higher requirements for the protection of cultivated land in China and also reflects the urgent need to carry out cultivated land resource accounting. In recent years, studies on the use of cultivated land have been quite rich and mostly focused on the utilization efficiency and carrying capacity of cultivated land (He et al., 2011; Wang and Li, 2014; Chen et al., 2019; Han and Zhang, 2020). And ecological footprint model is more and more used to analyze the utilization of natural capital of cultivated land because of its intuitive and concise characteristics (Shi et al., 2013; Qian et al., 2018; Wang et al., 2018).

The ecological footprint is a method of accounting for the physical amount of natural capital, which converts the natural capital provided by ecosystems into the geographical space with ecological functions and biological productivity, also called "ecological occupation" (Wackernagel and Rees, 1998; Rees, 2018). This method can achieve an unified description of all kinds of natural capital, and with the introducing of equilibrium factors and yield factors, the accumulation and comparative analysis of all kinds of natural capital in each region can be carried out (Fang and Heijungs, 2012; Shi D, 2016; Jin and Liu, 2017; Hong et al., 2020). However, as the research progresses, the traditional two-dimensional ecological footprint cannot meet the needs of structural analysis of natural capital stock and flow, and cannot reflect intergenerational human consumption of arable land, so the ecological footprint model begins to move from two-dimensional to three-dimensional. The three-dimensional ecological footprint model is based on the two-dimensional ecological footprint model, which introduces the footprint depth and footprint breadth to measure the total ecological footprint (Niccolucci et al., 2009; Fang and Heijungs, 2012; Fang, 2013). The introduction of these two indicators not only overcomes the shortcomings of the traditional model that pays insufficient attention to the natural capital stock, but also enhances the comparability of ecological carrying capacity between different periods and regions. Moreover, although the three-dimensional ecological footprint model does not account for the physical quantity and value of natural capital directly, it can reflect the utilization and structural characteristics of natural capital stock and flow from the side, which meet the needs of natural capital analysis. In addition, compared with the absolute value analysis of the two-dimensional model, the relative and comprehensive values derived from the three-dimensional ecological footprint model, such as stock-flow utilization ratio, flow occupancy rate, "scissors differential", Gini coefficient of ecological footprint, etc., are more advantageous for in-depth analysis of the dynamics of ecology-economy relationship. Therefore, the three-dimensional ecological footprint model has been highly concerned and widely used in domestic and international academic circles (Fang and Li, 2012; Fang, 2013; Fang, 2015; Du et al., 2016; Ma et al., 2017; Yang and Hu, 2018; Wu et al., 2021). For natural capital accounting of cultivated land, it is necessary to pay attention to both the annual renewable resource and service flows, for example, the main agricultural products supply and ecological functions of cultivated land; and the stock consumption status, such as the area and capability of cultivated land. Thus, three-dimensional ecological footprint model has also been applied to the research of cultivated land use nowadays. For example, Jin et al. analyzed the utilization and ecological carrying capacity of cultivated land natural capital in Jiangsu Province by comparing the closed environment and the open environment, and found that the occupation of cultivated land natural capital in Jiangsu Province changed from the consumption stock to the consumption flow, and the sustainable utilization level of cultivated land was improved (Jin et al., 2020). Some research combine the improved ecological footprint model with the multi-objective programming model to analyze the sustainability of cultivated land under different use

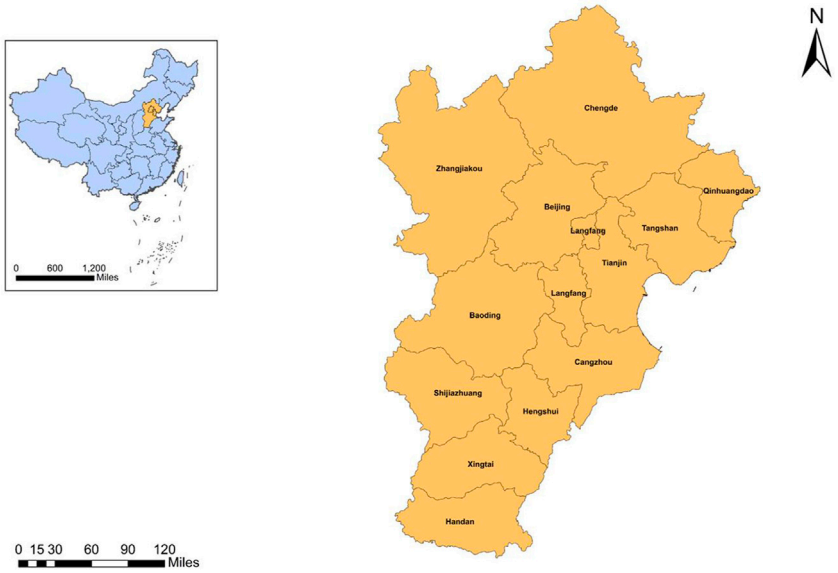

FIGURE 1
The study area.

scenarios (Li et al., 2020). However, these studies mainly focus on the description of the ecological carrying capacity of cultivated land, which is weakly related to policy making. In addition, some scholars have introduced three-dimensional ecological footprint model into ecological compensation of cultivated land (Su et al., 2014; Yang X. et al., 2019; Qian et al., 2022), but most of the research focuses on the amount of cultivated land ecological compensation, and there are few analyses from the perspective of fairness.

The Beijing-Tianjin-Hebei region is one of the three major urban agglomerations in China and an important carrier of the national regional coordinated development strategy. The Beijing-Tianjin-Hebei region has a dense population and is faced with serious resource shortage, ecological environment deterioration and unbalanced development, the gap between the economic and social development of Hebei and Beijing and Tianjin is known as a phenomenon called "black under the lamp". In terms of cultivated land, Beijing-Tianjin-Hebei region land use type is given priority to with farmland, but cultivated land for the middle-and-low-yielding fields, and the Beijing and Tianjin per capita cultivated land resources is far below the national average, and its huge economic size and population scale of agricultural products demand will lead to the cultivated land demand spillover, then need to depend on the vast fields of Hebei province. The environmental inequality in Beijing, Tianjin and Hebei has been verified (Ding and Wang, 2020). The results show that the environmental inequality between the Beijing-Tianjin-Hebei region has become more serious in recent years, with Beijing reaping more environmental benefits and Hebei bearing more pollution. Then how about the utilization of cultivated land natural capital in this region? Is it the same inequality occurred in utilization of cultivated land? This problem remains to be revealed, which is not only the purpose but also the originality of this research.

Therefore, the focus of this study is to conduct an accounting of the natural capital of cultivated land in the Beijing-Tianjin-Hebei region, analyzes the balance of natural resource utilization from the perspective of cultivated land, and complements the dimension of imbalanced development in this region from the perspective of natural capital utilization of cultivated land. Therefore, this study uses a three-dimensional ecological footprint model to account for and analyze the utilization of natural capital stocks and flows of cultivated land in the Beijing -Tianjin-Hebei region from 2009 to 2016 based on the breadth and depth of the footprint at the prefecture-level city scale, thereby providing evidence for cultivated land conservation, arable land ecological compensation, and coordinated and balanced regional development.

2 Study area and methods

2.1 Study area

Beijing, Tianjin and Hebei are located in the North China Plain, as "Capital Economic Circle" and one of the three major urban agglomerations in China (Figure 1). With unique location advantages, Beijing- Tianjin- Hebei region is not only the economic engine in northern China, but also

undertakes the national major development strategy. In terms of geography conditions, the Beijing-Tianjin-Hebei region covers an area of about 216,600 square kilometers, and the terrain in the region transitioning from west to east, north to south and mountains to plains, with the Bohai Sea in the east and the "North China Ecological Barrier" in the west. The natural resources in the whole region are abundant and widely distributed. The land cover types in the region are diverse, with wetlands, cultivated lands, construction lands, forest lands, and grasslands alternating from southeast to northwest (Liu et al., 2013), and the utilization of agricultural land shows a transition trend from plantation land in the southeast to forestry and grazing land in the northwest. Socioeconomically, the Beijing-Tianjin-Hebei region includes 2 municipalities, Beijing and Tianjin, and 11 prefecture-level cities in Hebei province, including Shijiazhuang, Tangshan, Baoding, Qinhuangdao, Langfang, Cangzhou, Chengde, Zhangjiakou, Handan, Hengshui, and Xingtai. The Beijing-Tianjin-Hebei region is a densely populated area in China, with a total population of 113.074 million in 2019, accounting for 8.1% of the national share, and the total population is expected to reach 120 million in 2020. The urbanization rate of the Beijing-Tianjin-Hebei region was 65.8% in 2018, 4.7 percentage points higher than in 2014. While the rapid economic development and urbanization, water resources depletion, air pollution, cultivated land degradation and ecological deterioration not only constrain the coordinated development strategy of Beijing-Tianjin-Hebei, but also limit the sustainable development of the region.

2.2 Data sources

This study takes cultivated land as object, and mainly accounts for the consumption ecological footprint of cultivated land. Consumer goods, i.e., the main types of agricultural products, are selected as grain, cotton, oilseeds, vegetables and fruits. The agricultural output data and population data of Beijing-Tianjin-Hebei region were obtained from China Agricultural Statistical Yearbook, Hebei Rural Statistical Yearbook, China Urban Statistical Yearbook, Hebei Economic Yearbook, and statistical bulletins of 13 prefecture-level cities; the global average agricultural production data were obtained from the Food and Agriculture Organization of the United Nations (FAO, http://www.fao.org); land use data were obtained from the Second National Land Survey and the annual National Land Change Survey. Since the localized parameters are more consistent with China's resource endowment and agricultural production, the equilibrium factors and yield factors used in the calculation of this paper refer to the results of Liu's study (Liu et al., 2010; Liu et al., 2013). In addition, due to the difficulty of obtaining agricultural consumption data, agricultural production data was used instead, and this may result in the calculation of the ecological footprint of cultivated land slightly higher than the actual value. For ecological conservation reasons, this paper refers to the recommendation of the United Nations World Commission on Environment and Development (WCED) and deducts 12% of the biodiversity conservation area in the calculation (Barnaby, 1987).

2.3 Research methods

In this study, a modified three-dimensional ecological footprint model is mainly used to portray the stock and flow utilization of natural capital of cultivated land (Fang, 2013). The calculation formula is as follows.

$$\boldsymbol{EF_{3D} = EF_{size} \times EF_{depth}} \tag{1}$$

In which, EF_{3D} is the three-dimensional ecological footprint, and EF_{depth} represents the depth of ecological footprint of cultivated land, and EF_{size} represents the breadth of ecological footprint of cultivated land. According to the three-dimensional ecological footprint theory proposed by Niccolucci (Niccolucci et al., 2009), the footprint breadth characterizes the level of human occupation of natural capital flows, indicating the actual area of ecologically productive land occupied within the limits of regional ecological carrying capacity, and has spatial properties. The footprint depth characterizes the level of human consumption of natural capital stock, indicating the cumulative human demand for resources beyond the biological carrying capacity, and has temporal attributes; it can be characterized as a multiple of the regional land area, that is, theoretically required to maintain the current level of regional resource consumption, or the time required to regenerate the regional resource consumption for 1 year under the same policy and technical conditions. The formula for calculating the breadth and depth of the ecological footprint of cultivated land are as follows.

$$\boldsymbol{EF_{size} = \frac{EF_{depth}}{EF}} \tag{2}$$

$$\boldsymbol{EF_{depth} = 1 + \frac{ED}{BC}} \tag{3}$$

$$\begin{aligned} \boldsymbol{ED} &= \boldsymbol{EF - BC = N\left(ef - bc\right)} \\ &= \boldsymbol{N\left(\sum_{i=1}^{n}\sum_{k=1}^{6} e_k \times \frac{c_i}{p_i} - \sum_{k=1}^{6}\left(r_k \times e_k \times y_k\right)\right)} \end{aligned} \tag{4}$$

Where ED denotes the ecological deficit or ecological surplus (hm^2), the EF denotes the total ecological footprint (hm^2), and BC denotes the ecological carrying capacity (hm^2), and N denotes the total population of the region, and ef denotes the per capita ecological footprint, and bc denotes the ecological

carrying capacity per capita, k denotes biologically productive land (k = 1,2,3...,6), and i denotes consumer goods category (i = 1,2,3,...,n), c_i denotes the per capita production of the resource of the i th consumer good, p_i denotes the world average production of consumer good i, r_k denotes the actual per capita area of biologically productive land of the k th category, e_k denotes the equilibrium factor of the k th type of biologically productive land, and y_k denotes the yield factor of the k th type of biologically productive land.

In addition, this research further introduces the flow occupancy rate and stock-flow utilization ratio to analyze the level of flow utilization in case of ecological surplus and the degree of stock capital depletion in case of ecological deficit, two indicators can be calculated as follows.

$$\boldsymbol{R_{flow}} = \frac{\boldsymbol{EF_{size}}}{\boldsymbol{BC}} \times \mathbf{100\%}\ (0 < EF_{size} \le BC) \tag{5}$$

$$\boldsymbol{R_{flow}^{stock}} = \frac{\boldsymbol{EF - EF_{size}}}{\boldsymbol{EF_{size}}} = \frac{\boldsymbol{ED}}{\boldsymbol{BC}} = \boldsymbol{EF_{depth}} - \mathbf{1} \tag{6}$$

When the natural capital flows are exhausted, the region is in an ecological deficit and starts to deplete the capital stock. Therefore, when the flow occupancy rate exceeds 100%, the larger the value, the higher the degree of stock capital depletion.

Since the Beijing-Tianjin-Hebei region has long been in a state of unbalanced economic and social development, the distribution of resource supply and consumption between regions also has a certain degree of unevenness. Therefore, in the context of the synergistic development of Beijing-Tianjin-Hebei, this research further introduces the Gini coefficient of ecological footprint (Fang and Heijungs, 2012) to evaluate the equity of natural capital utilization of cultivated land in the Beijing-Tianjin-Hebei region. The calculation formula is as follows.

$$\boldsymbol{G_{EF_{size}}} = \mathbf{2}\sum_{i=1}^{n}\boldsymbol{\lambda_{EF_{size,i}}} \times \sum_{i=1}^{n}\boldsymbol{\lambda_{pop,i}} - \sum_{i=1}^{n}\left(\boldsymbol{\lambda_{EF_{size,i}}} \times \boldsymbol{\lambda_{pop,i}}\right) - \mathbf{1} \tag{7}$$

Where $G_{EF_{size}}(0 \le G_{EF_{size}} < 1)$ indicates Gini coefficient of footprint breadth, $\lambda_{\mathrm{EF_{size,i}}}$ indicates i city footprint breadth as a proportion of the footprint breadth in the Beijing-Tianjin-Hebei region, the $\lambda_{pop,i}$ is the i th proportion of city population to the total regional population, and $\sum_{i=1}^{n}\lambda_{pop,i}$ is the cumulative proportion.

3 Results

3.1 Overall analysis of the three-dimensional ecological footprint of cultivated land

Since the breadth of ecological footprint characterizes the degree of utilization of natural capital flow and the depth of ecological footprint characterizes the degree of consumption of natural capital stock, the three-dimensional ecological footprint can form a "cylinder" if the breadth of footprint is regarded as the bottom and the depth of footprint as the length of a column. Ideally, if the flow of natural resources is sufficient to support economic and social development, the footprint depth is 0 and the cylinder does not exist, but in today's economic and social development transition period, the level of ecological governance and the efficiency of resource utilization are not yet able to reach this state. When the depth is greater than the breadth, the slender column is presented and the development is unsustainable; when the breadth is greater than the depth, the flat column is presented and the development is sustainable. Hence, during the transition period, the three-dimensional ecological footprint column should show a gradual flattening trend (Figure 2), i.e., the occupancy rate of natural capital flow increases and the consumption rate of natural capital stock decreases, so that the natural resources and ecological environment can be renewed, thus achieving sustainable regional development.

As shown in Figure 3, the depth and breadth of the cultivated land footprint in Beijing-Tianjin-Hebei region from 2009 to 2016 showed a cross fluctuating downward trend, and the depth curve was higher than the breadth curve most of the time. This implies that ecological management has played a positive role, but the overall natural capital use of cultivated land in the region is still in an unsustainable state.

Specifically, from 2009 to 2016, the ecological footprint breadth of each city in the Beijing-Tianjin-Hebei region, except Beijing and Tianjin, has slightly increased, and the ecological footprint depth has significantly increased and far exceeded the footprint breadth (Figure 4). This implies that the degree of depletion of natural capital stock of cultivated land in cities in the Beijing-Tianjin-Hebei region is increasing, but the level of flow utilization is still very low. While Beijing and Tianjin belong to "high ecological footprint depth-low ecological footprint breadth" cities, with the progress of natural resource utilization and governance level, as well as the transformation and development of the cities, Beijing has achieved a decrease in ecological footprint depth while keeping the ecological footprint breadth largely unchanged.

3.2 Decomposition analysis of the three-dimensional ecological footprint of cultivated land

3.2.1 Footprint breadth

Ecological footprint breadth portrays the strength of mobility of natural capital and the extent to which human activities use the flow capital (Du et al., 2016). Therefore, the higher the footprint breadth, the more sufficient the utilization of natural capital flows

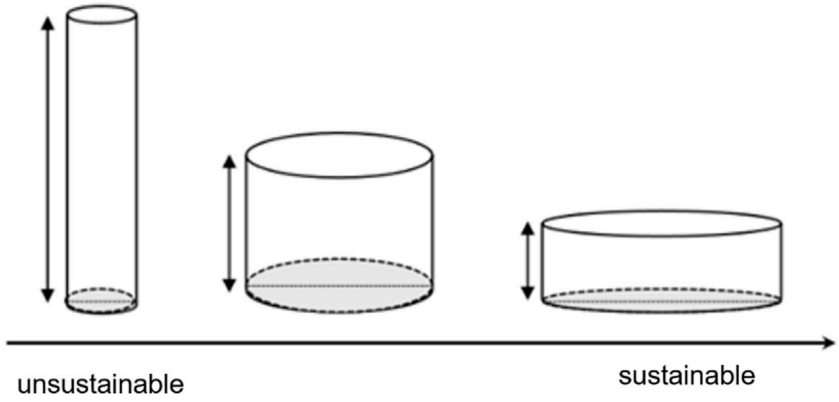

FIGURE 2
The relationship between three-dimensional ecological footprint and sustainable development.

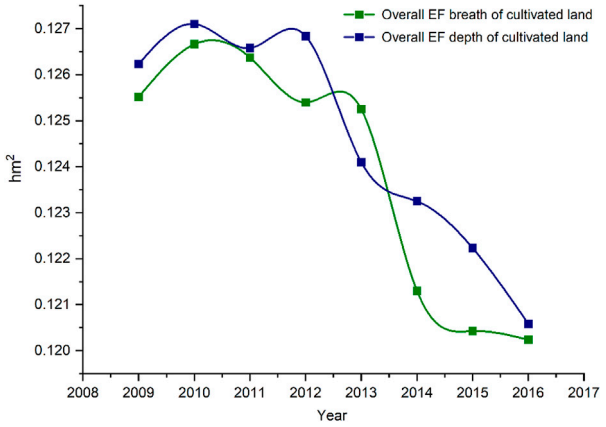

FIGURE 3
The overall trend of three-dimensional ecological footprint of cultivated land in Beijing-Tianjin-Hebei region.

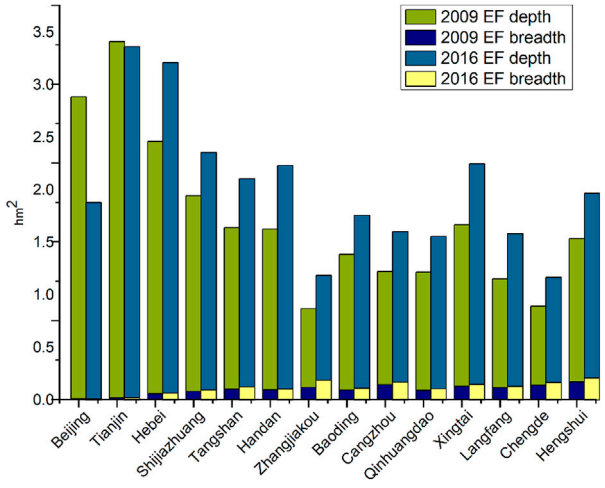

FIGURE 4
Comparison of ecological footprint depth in Beijing-Tianjin-Hebei region from 2009 to 2016.

by humans, and the consumption of capital stock will be reduced accordingly, and the lower the footprint depth should be. As can be seen from Figure 5, except for Zhangjiakou, the ecological footprint breadth of the provinces and cities in the Beijing-Tianjin-Hebei region are in a decreasing trend. That is, since the rate of ecological resource renewal is lower than the rate of human exploitation, their resource endowments cannot sustainably support economic activities, which in turn leads to a decrease in the available natural capital flows.

3.2.2 Footprint depth

Some cities have a high ecological footprint depth because their own natural resources are relatively scarce and their resources are renewed slowly, so economic activities will inevitably lead to the depletion of stock capital. However, some cities have high ecological footprint depths due to insufficient ecological protection and declining ecological carrying capacity of the region. For cultivated land resources, Hebei Province is a large agricultural and population province, and the per capita cultivated land resources have long been lower than the national average, and people lack the awareness of ecological protection of cultivated land, agricultural pollution is always been neglected, and the use of pesticides, chemical fertilizers and mulch is increasing by year. The massive and unreasonable use of agricultural inputs such as pesticides, fertilizers and mulch, coupled with unreasonable irrigation methods, has led to serious

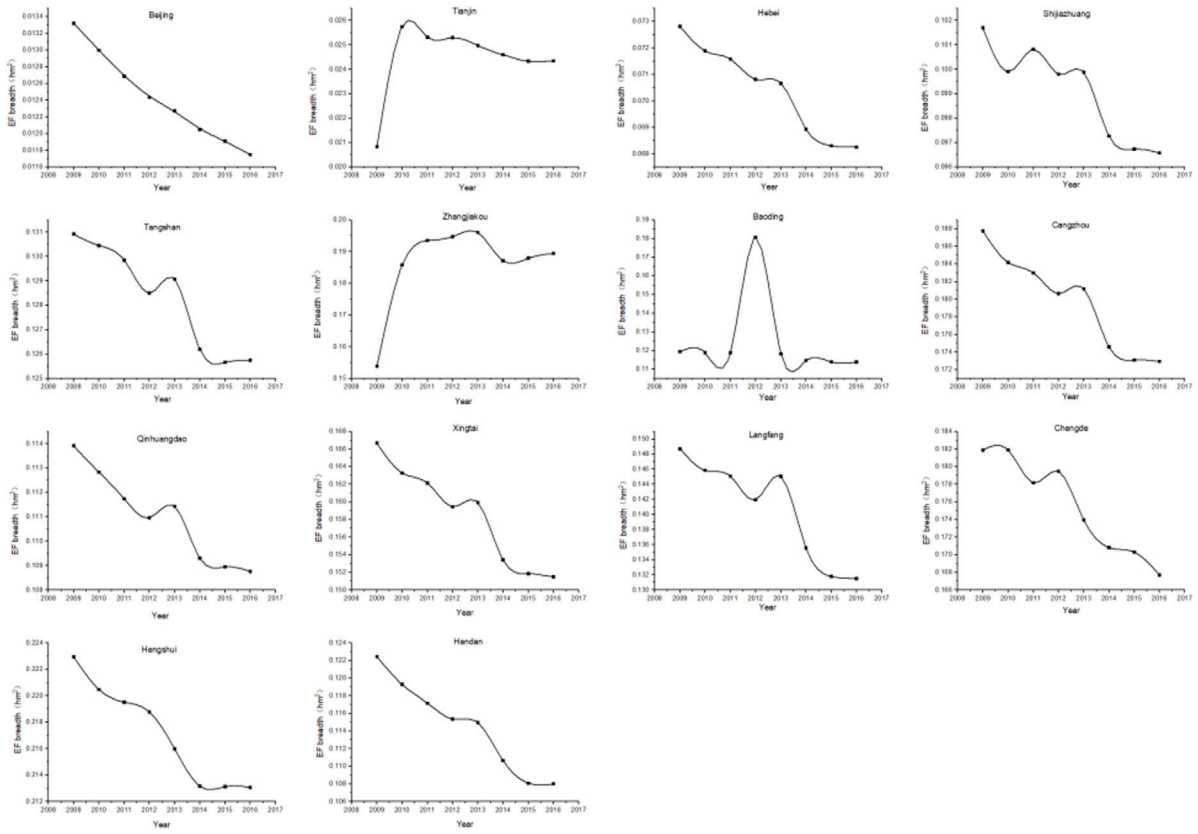

FIGURE 5
The trend of ecological footprint breadth of cultivated land in Beijing-Tianjin-Hebei region.

degradation of soil quality, prominent agricultural environmental pollution problems in some areas, and a decline in the ecological carrying capacity of cultivated land, thus leading to the phenomenon of high ecological footprint depth of cultivated land in most cities in Hebei Province. However, after years of cultivated land protection and ecological management, the ecological footprint depth of cultivated land has significantly decreased in many places in Beijing, Tianjin, Shijiazhuang, Tangshan, Qinhuangdao, Chengde, Hengshui, etc. (Figure 6).

3.3 Analysis of the three-dimensional ecological footprint structure of cultivated land

3.3.1 Flow occupancy rate

Capital flows do not reduce the total amount of wealth, which means sustainability for the ecosystem (Hicks, 1946). The occupancy rate of natural capital flows reflects the use of natural capital flows in a city or region. Under the ideal level of resource utilization technology and management, natural capital flows should be able to meet the natural material needs of economic activities, i.e., the flow occupancy rate is less than 100%. However, the results show that only Zhangjiakou and Chengde in the Beijing-Tianjin-Hebei region have controlled the flow occupancy rate to under 100% and achieved self-sufficiency in natural capital flow supply (Table 1). The remaining 85% of the cities, however, have reached 100% flow occupancy, indicating that the annual flow of products and services generated by the cultivated land in the region can no longer meet the needs of economic development for resources and environment, which needs to be compensated by flows from other cities or regions. It should be noted that natural capital flows of cultivated land are somewhat different from the general natural capital flows. Natural capital flow is the difference between the beginning and the end of the natural capital accounting period, and its source is natural capital, mainly the change of renewable natural capital. In contrast, cultivated land, as a non-renewable resource, is difficult to increase in quantity. Therefore, in addition to the increase or decrease of the quantity, the natural capital flow of cultivated land can also be understood as a qualitative change, which alter accordingly with the

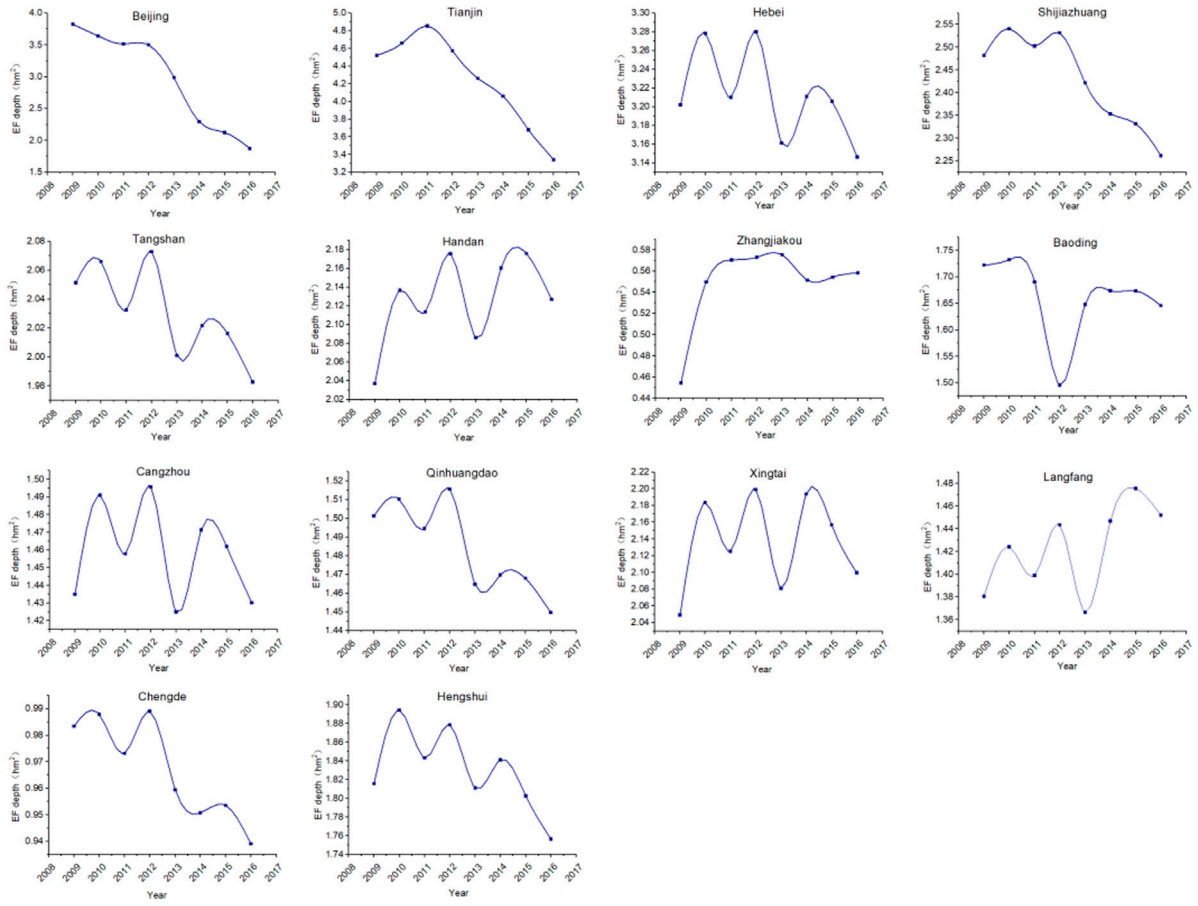

FIGURE 6
The trend of ecological footprint depth of cities in Beijing-Tianjin-Hebei region.

TABLE 1 The occupancy rate of natural capital flow of cultivated land in Zhangjiakou and Chengde.

	2009	2010	2011	2012	2013	2014	2015	2016
Zhangjiakou	45.44	54.97	57.05	57.30	57.52	55.12	55.42	55.83
Chengde	98.34	98.78	97.32	98.90	95.93	95.07	95.35	93.91

transformation of cultivated land use and changes in plantation technology and land reclamation technology.

3.3.2 Stock-flow utilization ratio

Natural capital consists of two components: flows and stocks. The flow represents the annual renewable resource flow and its ecological service supply, and the stock capital is consumed as a supplement when the flow is exhausted. The inability of the flow to meet the needs of economic activities implies the depletion of the natural capital stock. Since most cities in the Beijing-Tianjin-Hebei region have a flow utilization ratio of 100%, it cannot reflect the stock depletion status. Therefore, this study further introduces the stock-flow utilization ratio for in-depth analysis.

Figure 7 shows the stock-flow utilization ratio of cultivated land natural capital in the Beijing-Tianjin-Hebei region in 2009 (part A) and 2016 (part B). From 2009 to 2016, the consumption of natural capital stock of cultivated land in Beijing, Tianjin and Hebei basically maintained the spatial distribution pattern of "high in the south and low in the north" and "high in Beijing, Tianjin and low in Hebei". In terms of time, the consumption of natural capital stock of cultivated land in Beijing decreased significantly, while Langfang and Tangshan decreased slightly and Handan increased slightly. In the whole Beijing-Tianjin-Hebei region, except Zhangjiakou and Chengde, most of them are in a state of deep stock depletion. But, given the city's own resource endowment and stage of economic development, not all the natural capital stock

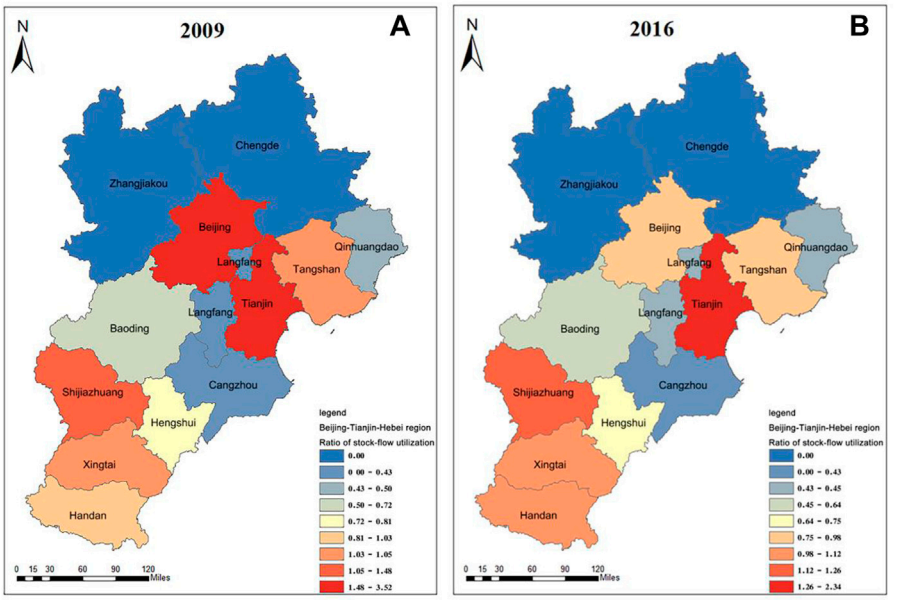

FIGURE 7
Stock-flow utilization ratio of cultivated land natural capital in the Beijing-Tianjin-Hebei region.

depletion is to be criticized. For example, municipalities like Beijing and Tianjin have large economies with a low share of primary industries. In Beijing, for example, the northwestern, northern, and northeastern parts of the city are mostly mountainous and supply Beijing's water sources, with low agricultural occupancy, mostly orchards in the mountains and crops on the plains. Agriculture is located in the southwest, south, southeast and east of Beijing, but with the development of the economy, most farmers no longer rely solely on agriculture. And with the expansion of the city, the amount of cultivated land in Beijing will gradually decrease. Therefore, after the ecological footprint model converts the main crop yield into ecologically productive land, the occupancy rate of its arable natural capital is necessarily high, which is in line with the characteristics of urban positioning and development stages. Hebei Province is a large agricultural province, and the production of major agricultural products such as grain, vegetables, meat, eggs and milk are among the highest in China, and its cultivated land utilization intensity is relatively higher than that of Beijing and Tianjin, especially in the southern cities such as Shijiazhuang, Xingtai and Handan, where the proportion of cultivation is much higher than that in the developed forestry and pastoral areas in the north. In the process of agricultural production, the reduction of cultivated land quantity, quality and ecological damage may lead to the increase of natural capital stock consumption of cultivated land. Zhangjiakou and Chengde formed an ecological conservation area in the Beijing-Tianjin-Hebei region, which has superior ecological resource endowment. Also, in this area, there is a great effort to return farmland ecologically. Converting cropland to forest or grassland allows production factors other than land to flow to more arable land, which can save investment, improve the food production conditions and improve the efficiency of input and output, so as to the region can always keep the cultivated land natural capital stock unchanged, and the flow is efficiently used. In addition, the increasingly serious phenomenon of "non-agricultural" of cultivated land in North China may also indirectly lead to the depletion of the natural capital stock of cultivated land. Due to the declining income from grain cultivation and frequent natural disasters, the proportion of grain cultivation in North China is decreasing and the proportion of cash crop cultivation is gradually increasing. Take vegetables as an example, the socio-economic development and the improvement of the living standard of residents lead to high demand for vegetables and good profitability. However, the cultivation of vegetables will lead to an increase in carbon emissions, use of fertilizer and mulch, as well as a decrease in land fertility and agricultural surface pollution, which will in turn reduce the ecological carrying capacity of cultivated land and cause the depletion of its natural capital stock.

3.3.3 Ecological footprint gini coefficient

In addition, this study analyzes the equity of natural capital flow appropriation of cultivated land in Beijing-Tianjin-Hebei regions by calculating the ecological footprint Gini coefficient of cultivated land and referring to a Gini coefficient evaluation criterion. The Gini coefficient of ecological footprint of cultivated land in Beijing-Tianjin-Hebei region was calculated (Table 2).

TABLE 2 Gini coefficient of cultivated land ecological footprint in Beijing-Tianjin-Hebei region.

	2009	2010	2011	2012	2013	2014	2015	2016
Ecological footprint Gini coefficient	0.419	0.388	0.395	0.397	0.396	0.382	0.383	0.380

TABLE 3 Comparison table of ecological footprint Gini coefficient and flow occupancy equity.

Ecological footprint gini system ($G_{EF_{size}}$)	$G \leq 0.2$	$0.2 < G \leq 0.3$	$0.3 < G \leq 0.4$	$0.4 < G \leq 0.5$	$G > 0.5$
Homogeneity	Highly balanced	More balanced	Relatively reasonable	More uneven	Highly uneven

According to the theory of regional unbalanced development, labor, technology and capital from various cities in Hebei Province tend to flow easily to Beijing and Tianjin, leading to the widening of regional development gap. Coupled with the inadequate regional agricultural market integration and factor flow mechanisms, the equity of the utilization of arable natural capital as a basic element supporting agricultural development is also skewed under the influence of the unbalanced development pattern of Beijing-Tianjin-Hebei. As the production base of grain, cotton, oil, vegetables and fruits in Beijing-Tianjin-Hebei region and the supply place to meet the demand of agricultural products from Beijing and Tianjin, Hebei Province has realized the transformation of economic value in the use of cultivated land, but also paid a certain price, i.e., the depletion of cultivated land, especially ecological depletion, caused by agricultural production is not compensated accordingly, which is the reason for the high Gini coefficient of ecological footprint of cultivated land in the region.

According to Table 3, the Gini coefficient of cultivated land ecological footprint in Beijing-Tianjin-Hebei region was 0.419 in 2009, which was in a relatively uneven state, but gradually improved after 2010. Although the Beijing-Tianjin-Hebei synergistic development strategy was not formally proposed in 2009, the concept of synergistic development of the region has been formed since "Langfang Consensus" (Wei Jinping and Wei, 2014). Under the guidance of the concept of balanced development and policy interventions in the region, the balance of natural capital utilization of cultivated land in Beijing-Tianjin-Hebei region shifted from more uneven to relatively even from 2010 to 2016, indicating a significant positive effect of regional ecological governance and cultivated land conservation.

4 Discussion

4.1 Comparison with previous studies

This study analyzed the utilization of cultivated land natural capital in Beijing-Tianjin-Hebei region based on three-dimensional ecological footprint model from the perspective of equity. There is a long history of inequality in this region, not only in terms of economic development and per capita income, but also in terms of resources and the environment, which has been noted in many studies (Hou, 2019; Li, 2021; Wang and Zhang, 2022). To some extent, the unbalanced economic development will lead to the uneven quota of resources and environment, which will cause serious ecological and environmental problems and hinder the sustainable and balanced development of the region. Urban development and expansion also tend to crowd out cultivated land and primary industries, and it is the surrounding areas that bear the brunt of these pressures. Thus, what makes this study unique is that we analyze the utilization of natural capital in this region from the perspective of cultivated land, a key type of natural capital, which can combine the results with the cultivated land protection and utilization, coordinated development, equitable development and ecological compensation of cultivated land in this region, so as to provide a basis for policy making.

This study analyzed the direct utilization of cultivated land natural capital, and found that the utilization level of cultivated land natural capital flow in the Beijing-Tianjin-Hebei region was generally low, and most cities had serious consumption of cultivated land natural capital stock. From the perspective of the whole region, the ecological use of cultivated land is in a relatively unbalanced state. Other studies evaluated the equity of cultivated land natural capital utilization in the Beijing-Tianjin-Hebei region from the perspective of virtual land, and reached similar conclusions as this paper. The cross-regional consumption of natural capital exists between regions, which is usually implied in the trade of products, which is not easy to be detected. Hebei is responsible for more natural capital consumption of cultivated land for the development of Beijing and Tianjin, especially Beijing. Pei et al. used ecological footprint model and regional input-output table in 2002 and 2007, and found that the social and economic development of Beijing has caused ecological pressure on the

land resources in the Tianjin and Hebei, and its development cannot be separated from the support of ecological productive land resources in the surrounding areas, such as agricultural land resources (Pei et al., 2016). Guo et al., using the regional input-output data of 2012, found that the utilization of cultivated land natural capital in Beijing, Tianjin and Hebei was unfair, and the development of Beijing and Tianjin made great use of virtual land in other cities in Hebei (Guo et al., 2020). Unfortunately, most of the data in these studies are cross-section data sets, which make it difficult to analyze the utilization trend of cultivated land natural capital through time series. This study makes up for this shortcoming.

This study also reveals the relationship between the use of natural capital and ecological compensation of cultivated land, which provides ideas for ecological compensation of cultivated land. This study suggests that the excessive depletion of natural capital of cultivated land caused by the production of agricultural products can be used as a reference basis for ecological compensation of cultivated land across regions, thus supporting the realization of ecological value of cultivated land. When an ecological deficit occurs in a region, it indicates that human activities in the region have imposed a heavy burden on the ecological environment and the ecological condition is not optimistic. When a region produces ecological surplus, it means that the consumption of ecological resources in the region is reduced and the ecological condition is guaranteed. Therefore, through this study, the supply of regional resources and environment as well as the difference of regional resource supply and demand can be understood. In addition, by calculating the three-dimensional ecological footprint of natural capital of cultivated land, it is also possible to identify the ecological surplus and ecological deficit areas of cultivated land spatially and estimate the utilization status of cultivated land resources, thus providing a basis for optimizing the utilization pattern of cultivated land resources and the formulation of cultivated land protection policies. Many studies have shown that this idea is feasible (Su et al., 2014; Zhao et al., 2017; Qian et al., 2022). However, after identifying the ecological supply and ecological benefit areas, these studies used the value of ecosystem services to calculate the amount of ecological compensation for cultivated land, which is still open to question in future research. Because most of the total ecosystem service value of cultivated land used in these studies often includes non-market value such as cultural value, the amount of which differs greatly from the economic value of cultivated land due to the calculation method, so it is not suitable to be used as the calculation basis for the amount of ecological compensation of cultivated land at this stage. Due to the limitation of space, the mechanism and calculation of ecological compensation for cultivated land will be discussed in another paper.

4.2 Limitation and future topics

The three-dimensional ecological footprint portrays the extent to which agricultural production uses the natural capital flows and stocks of cultivated land. When agricultural production in a region causes overuse of cultivated land, the flow is depleted and the stock declines. Since the flow of products provided by natural capital of cultivated land is dominated by primary agricultural products such as grain, cotton, oilseeds, vegetables and fruits, these agricultural products will be traded across regions in addition to supplying local residents for consumption. For example, the delivery of agricultural products from Zhangjiakou, Chengde and Handan to Beijing actually consumes the natural capital of the cultivated land in the place of origin. The price of agricultural products in the trading process often only includes planting costs, transportation costs, technique, labor, etc., without ever considering ecological costs. And this part of the ecological cost gap should be compensated accordingly. However, due to the difficulty of obtaining agricultural products trading data, the flow of natural capital of cultivated land between cities along with product trade is not considered. The latest interregional input-output table combined with ecological footprint model can be considered in further study.

The yield factors used in the calculation of the three-dimensional ecological footprint in this paper are at the provincial scale, which may not be accurate enough when calculating the ecological footprint of prefecture-level cities. The results will be closer to the actual situation if we re-calculate the yield factors in prefecture-level based on net primary productivity, etc., which is also a topic that we will further study in the future.

5 Conclusion

This paper presents a systematic analysis of the natural capital of cultivated land in Beijing-Tianjin-Hebei region from 2009 to 2016 based on a three-dimensional ecological footprint model from ecological footprint theory. It is found that from 2009 to 2016, the ecological footprint breadth of cultivated land in Beijing-Tianjin-Hebei region is generally low and the footprint depth is generally high, and the ecological footprint depth of cultivated land in the region as a whole tends to increase, except for some cities with outstanding resource endowments (e.g., Zhangjiakou and Chengde) which can achieve self-sufficiency in natural capital flow, 85% of cities have experienced depletion of natural capital flow of cultivated land and increased depletion of natural capital stock. From the overall and long-term perspective,

the creation and utilization level of natural capital flow of cultivated land in the Beijing-Tianjin-Hebei region needs to be improved, and the ecological protection of cultivated land needs to be further strengthened. In addition, in terms of equity, the ecological balance of cultivated land in the Beijing-Tianjin-Hebei region shifted from relatively uneven to relatively even from 2009 to 2016, indicating that the collaborative management of cultivated land protection and ecology in Beijing-Tianjin-Hebei achieved initial results. Therefore, in the future collaborative development of Beijing-Tianjin-Hebei, it is more important to focus on ecological protection and collaborative function of regional cultivated land, and to promote the sustainable use of natural capital and coordinated regional development according to the local conditions and policies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

HZ was responsible for conceptualization, methodology, investigation, formal analysis, original draft writing, review, editing and visualization. YZ was responsible for methodology, formal analysis and original draft writing. D-LZ was responsible for review and editing, project administration and funding acquisition.

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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.

Publisher's note

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