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Research on china's ecological surplus and deficit and ecological compensation mechanism

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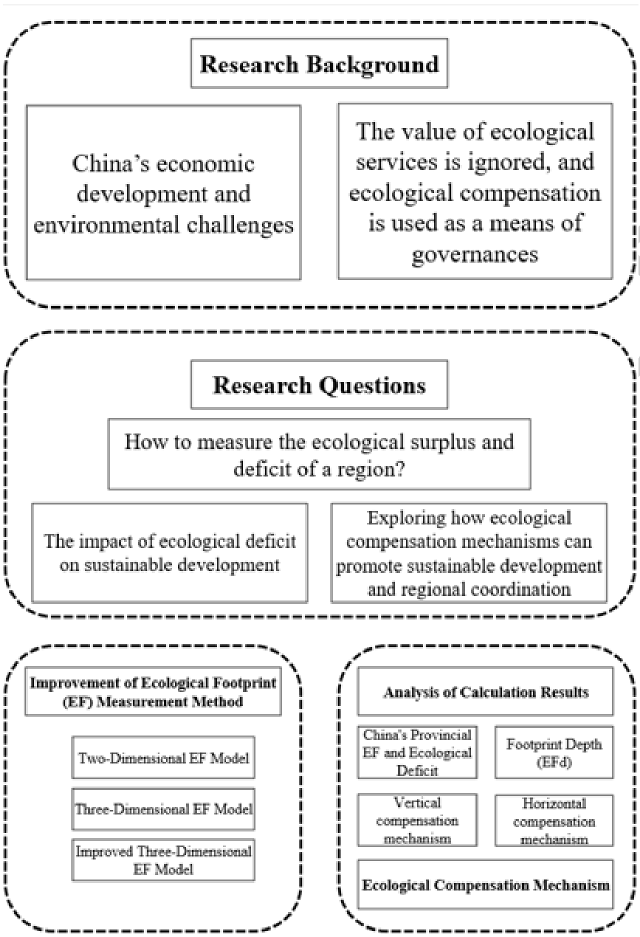
Graphical abstract



Abstract

In order to investigate the ecological surplus and deficit of each province in China and dissolve the ecological deficit, this paper uses the improved three-dimensional ecological footprint (EF) model to measure the ecological deficit in each province, estimates the value of ecological services by using the equivalent factor method, and measures the value of ecological services corresponding to inter-provincial trade by using the inter-provincial input-output table, and thus constructs two kinds of vertical and horizontal ecological compensation mechanisms. The research conclusion is as follows: ecological deficits exist in all provinces of China from 1990 to 2019, and the vast majority of provinces are experiencing an upward trend in ecological deficits. The footprint depths are all greater than 1, and there is always an overdraft of the ecological capital stock by economic development, particularly in the developed eastern regions. From the perspective of vertical compensation, the cumulative average number of overdraft years in each province during the study period is 87.3 years, which is very high, and the willingness and ability to compensate for future generations are limited. From the perspective of horizontal compensation, except for Tibet, Qinghai, Inner Mongolia and Xinjiang, most provinces receive less compensation than they pay, which can be moderately compensated through central financial transfers payments.

Keywords: Ecological surplus and deficit; Ecological compensation; Ecological footprint; Ecological service value; Inter-provincial input-output table

1. Introduction

Since the reform and opening up, China's economy has made remarkable achievements, but the rough economic growth mode has also brought about serious problems of resource shortage and pollution (Zhou *et al.* 2025; Ma and Appolloni 2025). In this context, scholars and governments have begun to re-examine the contribution and constraints of natural resources and environmental factors to economic and social development (Lei and Xu 2025). The natural ecosystem, as the life support system of the earth, is the foundation for human survival (Barnosky *et al.* 2014). In the process of developing and utilizing the natural resources, direct market value is mainly emphasized, while the value of ecological services is lack of attention. Ecological economists believe that the study of ecological service value can help to rationally solve the distribution of natural resources among different utilization purposes (Farley 2012). The use of economic means to regulate human development and utilization of natural ecosystems is conducive to the effective protection of ecosystems (Ma *et al.* 2025a; Rees 2003).

As China continues to pursue economic reforms and innovation across various sectors (Ma *et al.* 2025b; Ying *et al.* 2025). There is an increasing recognition that sustainable development requires not only technological and financial innovation but also a fundamental shift towards valuing ecological services. To focus on the value of ecological services in a region, the first step is to measure the ecological surplus and deficit. Previous studies use the ecological carrying capacity to characterize the ecological supply of a certain region and the EF to reflect its ecological demand, and the difference between them is the ecological surplus and deficit (Wang *et al.* 2024). Negative ecological surplus and deficit is called ecological deficit, that is, ecological consumption exceeds the normal supply of the year, and the sustainable development requires that it must be compensated. Ecological compensation provides a system of compensation, restoration and integrated management related to the damage of ecosystems and natural resources caused by human activities (Zhang *et al.* 2021). It is a policy means to improve the relationship between socio-economy and natural environment. An in-depth exploration of the ecological compensation mechanism is of great value in promoting sustainable development of China's economy and regional coordination (Lei 2024).

2. Literature Review

2.1. Research on ecological surplus and deficit

The study of ecological surplus and deficit begins with the measurement of natural capital. Unlike economists who are keen on value measures, ecologists prefer non-value measures of natural capital, especially the EF model proposed by Wackernagel and Rees (1997). The EF is vividly likened to "the imprint left on the earth by a giant foot carrying the cities, factories, fields, and so on created human beings". The method aims to reveal the demand of human activities on the biosphere (Smil 2011), use the productive land area of various organisms to characterize the natural capital, extrapolate the ecological demand through the resource consumption corresponding to the annual consumption, and then compare it with the ecological carrying capacity to determine the ecological surplus and deficit. With the advantages of simplicity, intuition, and ease of comparison, the EF method is widely used at the macro level (Wackernagel and Rees 1997) and formed a standardized national footprint accounting, which powerfully promote the integration and complementarity of economics and ecology. Given the difficulties of the ecological deficit in revealing the impact on the stock of natural capital, Niccolucci *et al.* (2009, 2011)introduces the footprint depth to construct a three-dimensional EF method. Although there are still some doubts, the EF method is continuously improved and become the mainstream method in this field.

Despite its wide uptake, the EF approach has attracted sustained methodological criticism. Scholars argue that EF relies heavily on controversial assumptions about equivalence and yield factors, the conversion of carbon emissions to hypothetical "forest sink" area, and aggregation across incommensurable land-use categories, which may distort both absolute magnitudes and cross-regional comparisons (Fiala 2008; Kish and Miller 2025; van den Bergh and Verbruggen 1999). Recent debates further contend that the global "overshoot" result is highly sensitive to the assumed carbon sequestration rate and that EF mixes stock-flow dynamics in ways that can obscure policy signals (Syrovátka 2024; Van Den Bergh and Grazi 2015). In response, the Global Footprint Network has clarified accounting principles and updated the National Footprint Accounts, yet important issues remain regarding technology change, non-renewable resource depletion, and spatial heterogeneity in biocapacity. A critical reading of this debate is therefore essential before adopting EF as the core metric in this study.

To extend the multidimensional measurement of ecological capital, drawing on the EF approach, biodiversity footprint (Ji *et al.* 2025), water footprint (Rodríguez *et al.* 2024), energy footprint (He *et al.* 2022), carbon footprint (Rondoni and Grasso 2021), nitrogen footprint (Liu *et al.* 2021), and chemical footprint (Hogan *et al.* 2023) are developed. The expansion of footprints family helps to reveal the balance of ecological use (Fang *et al.* 2014). Building on this "family of footprints," water (Hoekstra and Mekonnen 2012), nitrogen (Leach *et al.* 2012), and biodiversity footprints (e.g., (Bjelle *et al.* 2021)) have advanced consumption-based and MRIO-linked assessments. However, integrating heterogeneous footprint indicators into a single welfare-relevant judgment remains challenging due to unit incompatibility, double counting risks, and divergent system boundaries, which calls for transparent multi-indicator dashboards rather than a single composite index (Read *et al.* 2022).

However, there are still great challenges in integrating various footprint information to form an overall judgment, this constitutes an important development direction for future research.

2.2. Research on ecological compensation

Ecological compensation refers to the reward for ecosystem protection and the punishment for ecosystem destruction, and as a new resource management model, it becomes an important ecological resource protection tool in the international arena (Gao *et al.* 2025). Research on ecological compensation begins in the United States, Australia, and Germany (Du *et al.* 2023), and now expands into the fields of land resources (Barbier 2020), water resources (Tripathy and Mishra 2024), and forestry resources (Sun and Li 2021), covering the theoretical basis, compensation methods, policies, standards and other aspects. Among them, the compensation standard is the core content of ecological compensation, which becomes the focus of academic research (Wang *et al.* 2022).

Internationally, ecological compensation has evolved under the umbrella of Payments for Ecosystem Services (PES), biodiversity offsetting, and "no-net-loss" policies. Foundational reviews highlight that PES design should

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emphasise conditionality, additionality, and cost-effectiveness, with careful attention to leakage and permanence(Brander *et al.* 2024; Jack *et al.* 2008). Credible causal evidence is growing: randomised evaluations show that well-targeted PES can significantly reduce deforestation in the short run, though long-term financing and monitoring remain open questions (Ferraro and Pattanayak 2006; Jayachandran *et al.* 2017). Equity has emerged as a central design criterion because distributional choices shape participation and environmental outcomes, implying trade-offs and potential synergies between efficiency and fairness (Loft *et al.* 2019). In parallel, biodiversity offset schemes propose scientifically justified multipliers and landscape-level planning, yet face criticism over additionality, time-lag risks, and irreversibility (Bull *et al.* 2013).

The commonly used calculation methods of compensation standards mainly include three categories. (1) Opportunity cost method. Opportunity cost refers to the cost of giving up or losing economic development opportunities in ecosystem service supply areas in order to maintain ecological functions (Zhou *et al.* 2022). This method is widely recognized and is particularly applicable to situations where social and economic benefits cannot be directly estimated. (2) Willingness-to-pay method, which focuses on revealing people's willingness to pay or accept to improve environmental quality, but is greatly influenced by stakeholders' perception and education level (Dimal and Jetten 2021). (3) Ecological service value method, which determines the theoretical amount of ecological compensation based on the spatial and temporal variations of supply, regulatory, cultural and support system service values in different regions (Zhou *et al.* 2019).

Each standard-setting approach entails well-documented limitations. Opportunity-cost methods risk under-compensation where land users face liquidity constraints or hold option values that are not observed. Stated WTP suffers from hypothetical bias and stakeholder framing effects. Ecosystem service value transfer can double-count across supporting and regulating services and is highly sensitive to spatial heterogeneity and benefit-transfer error (Engel *et al.* 2008; Pascual *et al.* 2014). To enhance scientific validity, recent frontier practice recommends results-based contracts with clear baselines and monitoring, spatial targeting or auctions to reveal private costs, and explicit equity safeguards to mitigate exclusion of marginalised groups (Jack *et al.* 2008; Loft *et al.* 2019).

In addition, the game models of multi-government interaction (Li *et al.* 2022) and government-enterprise interaction (Ding *et al.* 2022) are proposed to analyze how ecological compensation mechanism can be implemented to achieve social optimality for each interest subject. Wang *et al.* (2022)constructs a game model to prove the necessity of combining vertical and horizontal ecological compensation. Gastineau *et al.* (2021) develops a normative research method for optimal environmental compensation in a spatial framework, but it does not yet address factors such as subsequent costs. The ecological compensation mechanism can realize the sustainable use of resources (Wang *et al.* 2025; Yang *et al.* 2022), however, it is still difficult to achieve a practical long-term ecological compensation mechanism. How to establish a reasonable ecological compensation standard urgently needs in-depth research.

2.3. Literature summary and assessment

The traditional EF models treat ecological surpluses and deficits inconsistently and fail to reveal changes in the stock of natural resources where there is an ecological surplus, which damages its analytical function. The existing methods of ecological compensation generally have the limitations of time and space scale, which weakens the relationship between the consumption of natural resources and socio-economics.

Drawing on existing research results, this paper seeks to make improvements and innovations in the following three aspects. (1) Improve the three-dimensional EF model, incorporate the ecological surplus and deficit into the unified analytical framework, which intuitively reflects the impact of the annual ecological service flow surplus and shortage on the change natural resource stock, and effectively reveals the dynamic change of natural capital. (2) Balancing vertical and horizontal ecological compensation mechanisms. Vertically, it is a short-term solution to make up for ecological deficits by overdraft the right to use the resources of future generations. Horizontally, based on the principle that both producers and users are responsible for resource consumption, the corresponding ecological value of inter-regional trade decomposed, and the ecological compensation is made from the using area to the producing area, which is a long-term strategy. (3) Drawing on the method of measuring implied carbon emissions from trade, the ecological value corresponding to inter-regional trade is measured with the help of the inter-provincial input-output table data.

3. Ecological surplus and deficit measurement and analysis

3.1. Improvements in EF measurement methods

The one-dimensional model of EF is measured by the area of biological productive land required for human survival and development. This definition only emphasizes the quantity of ecological demand and cannot be used for the analysis of ecological surplus a

nd deficit. Furthermore, the ecological carrying capacity is introduced, and compared with the EF, which constitutes the two-dimensional model of the EF.

3.1.1. Two-dimensional EF model

We calculate the EF by using a hierarchical summation method. First, for a given area, the demand for biologically productive land of a specific category for each type of consumer good is calculate separately:

$$A_{ij} = \left(C_j / N\right) / P_{ij} = \left(Q_j + M_j - X_j\right) / \left(N \cdot P_{ij}\right) \qquad (1)$$

Where A_{ij} is the amount of class *i* land needed to produce the per capita consumption of the *jth* product, which is in essence the EF generated by the per capita consumption of

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the product ($ef_{ij} = A_{ij}$); C_j is the physical consumption of the *jth* product in a certain region, which can be obtained by adding local production Q_j to imports M_j and then subtracting exports X_j ; P_{ij} is the amount of the *jth* product that can be produced per hectare of global class *i* land (*i* = 1, 2, ..6, represent land, grassland, forest land, water, construction land and fossil energy land)[1]; *N* is the population size.

Then, the land demand for the per capita consumption of all items is summed up to obtain the per capita EF (*ef*) of the region:

$$ef = \sum_i r_i A_i = \sum_i \left(r_i \sum_j A_{ij} \right) \tag{2}$$

For various land types, the ecological demand of the region for class *i* land can be obtained by summing the per capita consumption demand for all projects $ef_i = A_i = \sum_j A_{ij}$. Given that the functions and production capacities of different types of land are different, they cannot be added up directly, and it is necessary to introduce an equalization factor r_i to adjust this difference. Using the weighted summing mechanism $\sum_i r_i A_i$, the *ef* of the region is finally obtained. It is multiplied by the population size to obtain the total ecological footprint, $EF = N \cdot ef$.

The key feature of the two-dimensional EF model is the comparison with the ecological carrying capacity. The per capita ecological carrying capacity (*ec*) is:

$$ec = \sum_i \left(S_i \cdot r_i \cdot y_i \right) \tag{3}$$

Where S_i is the per capita area of class *i* biologically productive land in a region, y_i is the yield factor, which is used to adjust for the difference in productivity of various types of land in the region compared to the base case (e.g., the global hectare) on which the equilibrium factor is based[2]. The adjusted *ec* is comparable to the *ef*. It can be used to calculate the total ecological carrying capacity, $EC = N \cdot ec$.

Finally, the *ef* is subtracted from the *ec* to obtain the ecological surplus and deficit.

$$\begin{aligned} ed &= ef - ec \quad (if \quad ef - ec > 0) \\ er &= ec - ef \quad (if \quad ec - ef > 0) \end{aligned} \tag{4}$$

ed is the per capita ecological deficit and *er* is the per capita ecological surplus. Multiplying both by the population size to get the total ecological surplus and deficit: $ED = N \cdot ed$, $ER = N \cdot er$.

When *ec*>*ef*, the annual flow of product and service provided by the ecosystem is sufficient to support the development demand of the same period, and the stock of natural resources in the ecosystem will not decrease, or even increased at this time. However, when *ef*>*ec*, the flow of product and service provided by the ecosystem per year cannot meet human demand, and it is necessary to consume the stock of natural resources in the ecosystem, forming the occupation and overdrawing of the welfare of the offspring.

3.1.2. Three-dimensional EF model

Niccolucci *et al.* (2009) adapted a two-dimensional EF model to a three-dimensional model in order to better reveal the consumption and occupation characteristics of natural resource flows and stocks. The basic idea is to introduce EF size (EF^s) and EF depth (EF^d), which are used to decompose the EF.

$$EF = EF^s \cdot EF^d = \begin{cases} EF \cdot 1 & when\ EF \le EC \\ EC \cdot (EF / EC) & when\ EF > EC \end{cases} \tag{5}$$

Formula (6) can also be rewritten into the following equivalent form.

$$EF = EF^s \cdot EF^d = \min\{EF, EC\} \cdot \left(1 + \frac{\max\{EF - EC, 0\}}{EC} \right) \tag{6}$$

When $EF \le EC$, EF^s=EF, EF^d=1, the flow of ecosystem services can fully meet human demand without consuming the stock of natural resources. When $EF > EC$, EF^s=EC, $EF^d = EF / EC$, the resource stock must be depleted to make up for the shortfall in ecological flows. Therefore, $EF^d \in [1, \infty)$. The per capita volume relationship can be directly derived from the total volume equation: $ef = ef^s \cdot ef^d$. Per capita amount compared to the total amount, the EF^s is different ($EF^s = N \cdot ef^s$), and the EF^d is no different.

The three-dimensional model realizes the vertical extension of the EF study, which is conducive to clearly characterizing the cross-period allocation of natural resources. The EF^d has a temporal attribute, which can be accumulated year by year to reflect the total effect in the long term, and makes up for the deficiency of the two-dimensional model in explaining the degree of resource stock occupation, taking into account both the horizontal and vertical comparability. In particular, it turns the focus to the support mode of human ecological needs, which strongly promotes the research on how to effectively solve the problem of insufficient ecological service flows.

3.1.3. Improved Three-dimensional EF model

The traditional three-dimensional EF method focuses on ecological deficit, and the treatment of ecological surplus and deficit is inconsistent. Therefore, it is necessary to improve it.

3.1.3.1. Consistency improvement of surplus and deficit

The basic idea is that the EF^d is reflected by the EC, regardless of ecological deficit or surplus. Then, for any land type *i*, the EF^d is calculated as:

[1] For agricultural products, P_{ij} is relatively simple to calculate. However, for energy products, its calculation also requires additional conversion parameters.

[2] The equilibrium factor is used to adjust for comparability between different land categories in the same regions, and yield factor is used to adjust for comparability between the same land categories in different region s.

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$$EF_i^d = EF_i / EF_i^s = EF_i / EC_i \tag{7}$$

The overall EF^d of all land types in a region is also the ratio of its EF to its EC:

$$EF^d = \frac{EF}{EC} = \frac{\sum_i EF_i}{\sum_i EC_i} = \sum_i \frac{EC_i}{\sum_i EC_i} \frac{EF_i}{EC_i} = \sum_i W_i \cdot EF_i^d \tag{8}$$

Formula (8) shows that the overall EF^d is a weighted average of the EF^d of the various lands, the weights are the shares of the EC of various lands ($W_i = EC_i / \Sigma_i EC_i$).

According to the above definition, the value domain of EF^d is extended to (0, ∞). Taking 1 as the boundary, it can be divided into two parts: EF^d less than 1 corresponds to ecological surplus, EF^d greater than 1 corresponds to ecological deficit, EF^d equal to 1 corresponds to ecological balance.

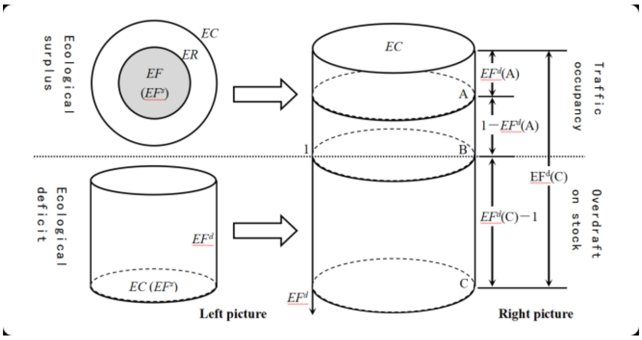

Figure 1. Improvement of the consistency of surplus and deficit of three-dimensional EF model

For intuitive understanding, a geometric illustration of the above improvements is given in **Figure 1**. The left figure shows how the traditional three-dimensional EF is depicted: it only measures the ecological footprint by the volume of cylinders when there is an ecological deficit (lower half), with the base area as the EF^s and the height as EF^d; in the case of ecological surplus (upper half), it is degraded into a two-dimensional model. The figure on the right shows the modeling method of the improved three-dimensional EF, where the volume of the cylinder reflects the EF regardless of the surplus or deficit. Below, several specific points are selected for illustration. The EF of point A is less than the EC (ecological surplus), where the EF^d is less than 1, indicating that the required ecological service flow is less than the supply within one year, and the flow surplus $EC(1\text{-}EF^d(\text{A}))$ is usually transformed into the growth of natural resource stock. Point B is just at the breakeven state, the annual ecological service flow of natural resources exactly meets the ecological demand of society, and at this time the stock of natural resources remains unchanged. The EF at point C is larger than the EC (ecological deficit), where the EF^d is larger than 1, indicating that the required ecological service flow is exceeds the supply within one year, and the flow gap $EC(EF^d(\text{C})\text{-}1)$ needs to be made up by overdraft of the stock of natural resources.

The extended three-dimensional model uniformly characterizes the ecological surplus and deficit in terms of the volume of cylinders, which can intuitively reflect the dynamic impact of the annual ecological service flow surplus and deficit on the stock of natural resources. The ecological surplus and deficit in a certain year will lead to the increase or decrease of natural resource stock, and then cause the same change of ecological service flow in the following year. This effect will have a significant impact through long-term accumulation, forming a virtuous interaction between ecology and economy under the pattern of sustainable utilization, and falling into a vicious cycle under the pattern of unsustainable utilization.

3.1.3.2. Integration of ecological surplus and deficit between land types

The traditional three-dimensional model considers that the ecological surplus and deficit of different land types are completely isolated, and prohibits the addition of ecological surplus and ecological deficit across categories. In view of the differences in the functions and productivity of various types of land, equilibrium factor should be introduced to make comparable adjustments when summing up the categorized EF. At this time, the calculation formula of the three-dimensional EF is:

$$EF = \sum_i r_i \cdot EC_i \cdot EF_i^d = N \sum_i r_i \cdot ef_i \tag{9}$$

Formula (9) is completely consistent with formula (2) after the introduction of the equalization factor to adjust for the productivity differences of different land types. The advantage is not in the calculation of EF, but in the stronger ability to analyze the ecological pressure and its dynamic impact.

3.2. Data description and parameter setting

3.2.1. Data description

Constrained by the availability of basic data, the time span of this study is set as 1990-2019. To calculate the categorical EF using formula (1), it is necessary to use data on the consumption of biological resources and energy products. The specific items of various products are shown in **Table 1**.

For biological resources, it is difficult to obtain consumption data directly from China's official statistics. Moreover, it is difficult to reflect the real ecological pressure of economic activities on a region by using consumption data. The consumption of resource-type products in some regions mainly comes from external transfers, and their own ecology is not affected accordingly. For some other regions, a large amount of resource-type products is exported, but the production process places a heavy pressure on local resources and causes serious ecological damage. The resource demand index can reveal the true ecological pressure generated by economic activities more effectively if it is changed from the volume of consumption to that of production. So, for bio-resource products, we use the production data in the calculation of provincial EF. Since China's official statistics (especially the regional energy balance sheets) can provide the data on the consumption of classified energy in each province, and the ecological impact of energy comes mainly from its use (combustion produces greenhouse gases and harmful substances), so it is more reasonable to use consumption data for energy products. The approach

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used in this paper has precedents in the existing EF literature (Luo *et al.* 2018).

Table 1. Biological resources and energy involved in the calculation of EF

Land type	Specific items on biological and energy resources
Arable land	Grain (rice, wheat, corn, beans, Potato products, others), vegetable, oilseeds (peanuts, rapeseed, sesame, others), cotton, hemp, sugar (beet, sugarcane), tobacco, silkworm cocoons, tea, pork, poultry meat, poultry eggs
Grassland	Beef, lamb, wool, milk
Woodland	Fruit (apple, orange, pear, grape, banana, persimmon, peach, jujube, melon, others), honey, timber, rubber, rapeseed, dried fruit (walnut, chestnut, others)
Water area	Fish, shrimp, crab, shellfish, other
Fossil fuel land	Coal, oil products, natural gas

Table 2. Global average land productivity base data and treatments

Product category	Data sources	Processing and calculation methods
Agricultural products	Food and Agriculture Organization of the United Nations (FAO).	According to the research period, the global average productivity (kg/ha) of agricultural products is selected for the corresponding year.
Lumber	According to the calculation results of Wackernagel and Global Footprint Network (GFN).	1990-2009 using Wackernagel measurements, 1.99 m^3/ha; 2010-2019 using GFN measurements, 1.81 m^3/ha.
Livestock products	Mainly refer to the data published by FAO in 2010. Cocoon data is from the Cocoon and Silk Office of the Ministry of Commerce and the "China Cocoon and Silk Industry Operation Report".	The global average productivity index from 1990 to 2019 is calculated using 2010 as the base period, and the global average productivity of livestock products is calculated using this index. The global average productivity of honey and cocoons is calculated separately. The global average productivity of honey is estimated by the number of global beehives published by FAO. A beehive needs 2-4 mu of plants that provide nectar, this paper takes the median value of 3. The average global productivity of silkworm cocoon is replaced by the ratio of silkworm cocoon production to the area of mulberry orchard in China.
Aquatic product	Taken from FAO & Fisheries Department.	The global inland sub-species fish production published by the Ministry of Fisheries, combined with the estimated area of global inland waters provided by FAO.

Table 3. Basic data and processing methods of average productivity of the land in China.

Indicator name		Data sources	Processing methods
Classification of land area (ha)	Arable land area, Grassland area, Woodland area, Water area, Construction land area	China Statistical Yearbook, China Land and Resources Statistical Yearbook, and 1-km raster data of land-use remote sensing monitoring issued by the Institute of Geographic Sciences and Resources of the Chinese Academy of Sciences for a specific year.	Garden land and woodland are combined as woodland, Urban, rural, industrial and mining and transportation land are combined into construction land, and water area and water conservancy facilities land are treated as water areas. The land-use area of each province is corrected by combining the yearbook data and remote sensing data to ensure the longitudinal comparability of the data.
Product output (10kt) Energy consumption (10kt/MCM)	Agricultural product production, timber harvesting volume, livestock output, aquatic product output, energy consumption	China Rural Statistical Yearbook, China Urban Statistical Yearbook, China Energy Statistical Yearbook, provincial statistical yearbooks. Agriculture, rural areas, farmers data from the EPS database.	Agricultural product production is taken directly from official statistics. Timber harvesting volume is converted using $1m^3$=0.75t. Aquatic product output includes the amount of aquatic products raised in inland waters and the amount of aquatic products caught. Energy consumption does not include the secondary energy consumption generated by the extraction and processing of primary energy.

In addition, it is necessary to determine the average productivity of the land, that is, the average yield per unit area of all kinds of agricultural products. It involves two parts of information: one is the average productivity of the

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land at the scale corresponding to the selected hectare standard, and this paper uses the global hectare standard, so the global average yield per unit area of each type of biomass products is needed, and the sources of the basic data and the processing methods are shown in **Table 2**. The second is the average yield per unit area of each type of biomass products and the average consumption per unit area of energy products in different regions of China, the sources of the basic data and the processing methods are shown in **Table 3**.

Table 4. Data source and calculation method of equilibrium factor and yield factor

Indicator name		Data sources	Processing and calculation methods
Equalizing factor	Arable land, grassland, woodland, water area, building land, Fossil energy land	From the Global Footprint Network (GFN), and compared with the World Wide Fund for Nature (WWF).	The equilibrium factor for the desired year is selected from the equilibrium factors for 1961 to 2019 published by the Global Footprint Network.
Yield factor	Arable land, grassland, woodland, water area, building land	Calorific value of products is from the Handbook of Agricultural Technology Economics (Revised), world average production of agricultural products is from FAO, production of agricultural products is from various statistical yearbooks.	The average productivity of calorific value of the corresponding land categories is calculated by converting all agricultural production to calorific value, the yield factor for each category is then obtained by comparing it with the global average productivity of calorific value of the corresponding land categories. Following NFA convention, the yield factor for construction land is taken from the yield factor for arable land.

3.2.2. Parameter setting

To calculate the EF and EC, need to determine several key conversion factors. Among them, the equilibrium factors are taken directly from the results published by GFN[3]. GFN also provides yield factors for China, but it is unable to provide yield factors at the provincial level in China, which need to be calculated using relevant data. Here, the energy-value method is used to determine the national and provincial yield factors. The calculation formula is:

$$y_i^k = \frac{\bar{E}_i^k}{\bar{E}_i} = \frac{E_i^k / S_i^k}{E_i / S_i} = \frac{\sum_j Q_j^k x_j / S_i^k}{\sum_k \left(\sum_j Q_j^k x_j \right) / \sum_k S_i^k} = \frac{\sum_j \frac{S_{ij}^k}{\sum_j S_{ij}^k} \frac{Q_j^k}{S_{ij}^k} x_j}{\sum_k \left(\sum_j Q_j^k x_j \right) / \sum_k S_i^k} \tag{10}$$

Where y_i^k is the yield factor of class *i* land in region *k*, E_i^k is the energy value (*J*) of the products produced by the class *i* land in region *k*, S_i^k is the area of class *i* land in region *k*, Q_j^k (*kg*) is the yield of various products of this class of land, x_j (*J/kg*) is the corresponding unit calorific value, $\bar{E}_i^k$ (*J/hm²*) is the average productivity of the class *i* land in region *k*. Similarly, we can compute the average productivity of the class *i* land in all regions ($\bar{E}_i$, taking the average productivity of land on a global scale). The basic data required for the above calculation is shown in **Table 4**.

The data used is taken from various statistical yearbooks in China, the China Economic and Social Big Data Research Platform, remote sensing monitoring data of land use, land survey data, forest inventory data, wetland survey data, the Economic Prediction System and World-Wide Fund for Nature (WWF).

3.3. Analysis of measurement results

3.3.1. EF and ecological deficit

Based on the preceding methods and data, China's *ef* and *ec* from 1990 to 2019 are calculated, and the difference between the two is the *ed* or *er*. Due to space constraints, **Table 5** briefly reports the results for the four nodal years.

The overall *ef* in China is on an upward trend, more than doubling from 1.19 gha (hectares per person) in 1990 to 2.51 gha in 2019. The *ef* of most provinces also shows a significant upward trend, and the pressure on resources and environment continues to increase. The national *ec* slowly increased from 0.52 gha to 0.68 gha from 1990 to 2019, but there are significant differences between provinces. The *ec* in the three northeastern provinces, five autonomous regions, Hainan, and Yunnan is higher and shows a significant upward trend, while the *ec* of developed regions such as Beijing, Shanghai, Jiangsu, Zhejiang, and Guangdong has decreased significantly. The main reasons of their low *ec* are high population density and large building land area. The *ec* in the rest of the provinces is mostly around 0.5 gha, and the trend of their *ec* is gentle.

[3] York University Ecological Footprint Initiative. National Footprint and Biocapacity Accounts, 2022 edition. Produced for the Footprint Data Foundation and distributed by Global Footprint Network. Available online at: https://data.footprintnetwork.org.

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Table 5. China and provinces' *ef* and *ec* (Unit: gha)

year / province	1990		2000		2010		2019	
	ef	***ec***	***ef***	***ec***	***ef***	***ec***	***ef***	***ec***
Beijing	1.88	0.41	1.72	0.31	1.47	0.21	0.95	0.10
Tianjin	1.77	0.37	2.15	0.36	2.90	0.35	2.72	0.43
Hebei	1.28	0.46	1.79	0.66	2.70	0.67	2.86	0.91
Shanxi	1.78	0.36	2.64	0.34	4.64	0.37	7.82	0.63
Inner Mongolia	1.74	0.82	2.22	0.96	6.84	1.82	11.75	2.62
Liaoning	1.81	0.52	1.94	0.48	3.14	0.63	3.65	0.71
Jilin	2.02	1.15	1.88	0.90	3.07	1.05	3.31	1.22
Heilongjiang	2.28	1.26	2.16	0.92	3.09	1.25	4.16	1.74
Shanghai	1.78	0.33	2.20	0.25	2.36	0.14	1.93	0.11
Jiangsu	1.34	0.60	1.66	0.62	2.52	0.56	2.55	0.52
Zhejiang	1.08	0.57	1.28	0.41	1.99	0.30	1.68	0.22
Anhui	0.99	0.52	1.46	0.66	2.15	0.69	2.49	0.72
Fujian	0.76	0.55	1.04	0.53	1.86	0.57	1.92	0.47
Jiangxi	1.03	0.61	1.11	0.56	1.69	0.65	2.02	0.67
Shandong	1.23	0.56	1.56	0.74	3.15	0.73	3.26	0.76
Henan	0.99	0.46	1.36	0.63	2.48	0.75	2.18	0.75
Hubei	1.40	0.78	1.80	0.75	2.52	0.77	2.33	0.73
Hunan	1.06	0.59	1.19	0.65	1.89	0.67	1.87	0.67
Guangdong	0.93	0.52	1.11	0.42	1.58	0.39	1.44	0.36
Guangxi	0.71	0.50	1.01	0.61	1.72	0.95	2.12	1.41
Hainan	0.58	0.53	0.92	0.61	1.55	0.65	1.81	1.24
Chongqing	0.57	0.23	1.19	0.39	1.87	0.39	1.64	0.40
Sichuan	1.09	0.57	1.04	0.47	1.64	0.49	1.48	0.56
Guizhou	0.77	0.26	1.14	0.30	2.11	0.35	2.30	0.42
Yunnan	0.74	0.42	0.94	0.45	1.75	0.61	1.80	0.86
Tibet	1.69	0.80	1.83	0.94	3.38	1.10	4.08	1.27
Shaanxi	0.86	0.37	0.88	0.38	2.20	0.49	3.37	0.55
Gansu	0.92	0.39	1.04	0.35	1.67	0.42	2.10	0.61
Qinghai	1.08	0.58	0.98	0.45	1.86	0.46	2.51	0.81
Ningxia	1.51	0.53	1.59	0.57	5.43	0.78	11.03	1.28
Xinjiang	1.58	0.82	2.04	0.85	3.51	1.08	6.55	1.45
Total	**1.19**	**0.52**	**1.37**	**0.55**	**2.25**	**0.67**	**2.51**	**0.68**

Note: 1990, 2000, 2010 and 2019 are selected as nodal years.

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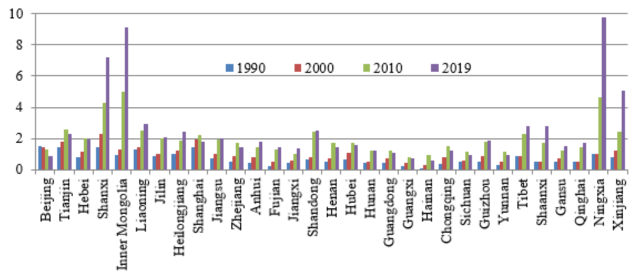

Figure 2. Per capita ecological deficit in each province (gha)

The *ef* is larger than the *ec* in both the country and the provinces during the investigation period, and there is ecological deficit. **Figures 2 and 3** give the *ed* and the total ecological deficit in each province. The differences in *ed* are obvious: Inner Mongolia, Ningxia, Shanxi, and Xinjiang take values as high as 2-4 times the national level. Hainan, Guangxi, Beijing, and Yunnan take values only half of the national level. The *ed* in most provinces are on an upward trend, as in the whole country, only Beijing has a clear downward trend, which stems from the fact that the decline in *ef* exceeds the decline in *ec*. The inter-provincial differences in the total ecological deficit are even more significant: Beijing, Tianjin, Chongqing, Guangxi, Hainan, Tibet, Gansu, and Qinghai, with a total ecological deficit of less than 40 (10^6 gha) and slow growth, and the ecological pressure in Hainan, Tibet and Qinghai is the smallest in particular. However, the causes are different: Beijing, Tianjin and Chongqing have higher levels of development and stronger ecological and environmental management capabilities. The service-oriented industrial structure of Hainan Province is more friendly to the ecology. The western provinces with lower ecological deficits mainly benefit from their small population and economic scale. The eight provinces with total ecological deficits exceeding 120 (10^6gha) and rapid growth are Hebei, Shanxi, Inner Mongolia, Jiangsu, Shandong, Henan, Guangdong and

Xinjiang. The rapid increase in their ecological deficits mainly stems from the rapid growth of their EF, which is mainly driven by the large demand for fossil energy caused by economic growth.

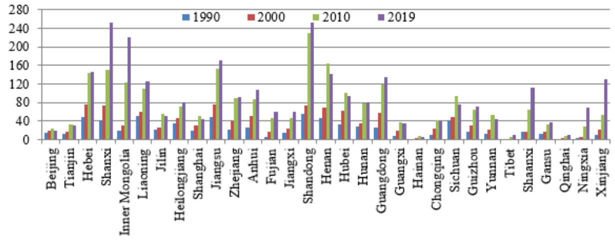

Figure 3. Total ecological deficit in each province (10^6 gha)

3.3.2. Footprint depth

According to the improved three-dimensional EF model, the EF^d is equal to the EF divided by the EC, which reflects the number of years of ecological service flow needed to support the EF of a given year. If the value is less than 1, it indicates that the flow of services provided by the ecosystem in the current year is still in surplus, and not only will it not be overdrawn, but will also increases the accumulation of stock. If the value is greater than 1, it indicates that there is a gap in the flow of ecosystem service in the current year, and it needs to overdraw the ecological capital stock. The EF^d can be cumulatively added vertically, and for regions with a long-term ecological deficit, this indicator can reveal the damage to intergenerational equity caused by accumulated ecological capital liabilities.

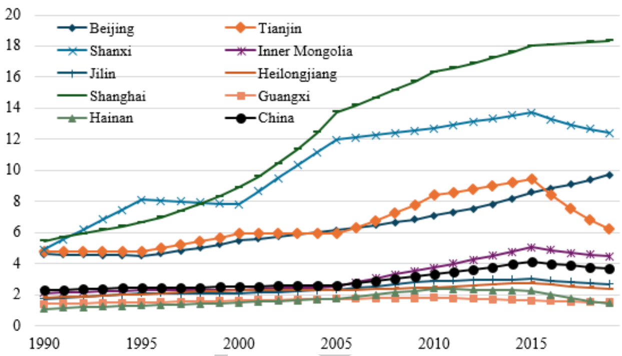

Figure 4. The trend of the EF^d in China and provinces from 1990 to 2019

Figure 4 shows that from 1990 to 2019, China's EF^d shows an overall upward trend, with a rise gently before 2005, then increasing at a higher rate and reaching a peak of 4.12 in 2015[4], and then slowly declining. The EF^d is greater than 1 during the investigation period, indicating that China's economic development has always been in overdraft of the ecological capital stock. There are obvious differences among provinces, and municipalities such as Shanghai, Beijing and Tianjin have limited EC and high EF^d. The footprint depth of Shanghai has climbed sharply from 5.5 in 1990 to 18.4 in 2019, which cannot be supported by its own EC alone. The highest EF^d in Shanghai is due to the fact that it is the economic center of China and a highly populated area. Human activities generate a large amount resource consumption, which intensifies the ecological pressure. At the same time, due to its smaller land area, the EC is very low. In view of Shanghai's high level of economic development and superior geographical location along the coast and river, its resource demand can rely on the vast economic hinterland, although the EF^d is high, it has not caused serious loss of its own ecological capital stock. Shanxi's EF^d is also very high, rising from 4.9 in 1990 to 12.4 in 2019. The main reason is that Shanxi Province is rich in coal resources, the industrial production is mainly heavy industry, and it has also undertaken a lot of high energyconsuming industries from the eastern developed areas, which makes its total energy consumption very large, and its EF far exceeds its EC. However, its level of economic development is not sufficient to constitute radiation and absorption to other regions, and thus its excess demand for ecological services is mainly met by means of stock overdraft. The EF^d of Jilin, Heilongjiang, Guangxi, Hainan and other provinces has been fluctuating around 2, putting less pressure on the ecological capital stock. The provincial differences in EF^d depend not only on resource endowment, but are also more closely related to the specific level of socio-economic development. Since 2015, the EF^d of the whole country and most provinces has decreased, which is a favorable change to reduce ecological pressure, but the long-term accumulation of ecological debt has caused great harm to China's sustainable development. There are two feasible ways to resolve this: one is vertical compensation, which is to use the ecological services of future years in advance by drawing on the ecological capital stock. The other is horizontal compensation, using the ecological value implied by the product of spatial trade transfer to make inter-provincial value compensation.

4. Vertical compensation mechanism for ecological deficit

4.1. Basic idea

For regions with abundant natural resources, because of their large resource endowments, even if the annual ecological consumption exceeds the normal supply for that year, it can still be made up by utilizing the stock. For example, the use of water resources in North China has long exceeded the natural carrying capacity, and over-exploitation of groundwater has become an emergency solution. As the EF^d can reflect how many years of ecological service flow is needed to support the EF of a certain year, its subtraction by 1 gives the number of years of vertical overdraft (For example, if the EF^d of Shanghai is 18.4 in 2019, it needs to be prepaid for 17.4 years of ecological services to compensate for the ecological deficit). Therefore, for regions with long-term ecological deficits, the number of years of vertical overdraft can be used to reveal the damage to intergenerational equity caused by cumulative ecological capital liabilities.

[4] In order to meet the needs of economic development in 2015, ecological services exceeding the supply capacity of the year by 3.12 years require the overdraft of ecological capital stock to support them.

4.2. Analysis of the degree of vertical overdraft

Figure 5 shows that the accumulated overdraft years of each province in 1990-2019 are generally very high. Guangxi and Hainan, which have the lowest degree of overload, also have a cumulative value of about 20 years. The average overloading degree of all provinces is 87.3 years. The cumulative value of the number of overdraft years in Liaoning, Zhejiang, Guizhou, Ningxia, Beijing, and Tianjin is more than 100 years. The degree of overdraft in Shanxi is 280.7 years, and it is as high as 410.7 years in Shanghai. Such severe overloads are mainly maintained by vertical overdrafts.

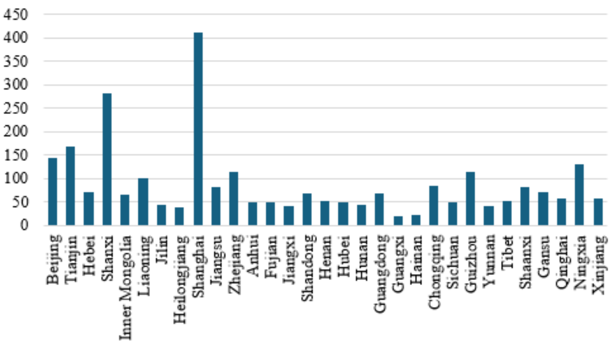

Figure 5. Cumulative value of overdraft years in each province from 1990 to 2019

The vertical overdraft of ecological deficits in the provinces lacks not only the willingness to compensate the younger generations, but also the ability to do so. Most provinces, in this way, are unable to solve the ecological deficits caused by overconsumption of resources. Vertical compensation is only a short-term emergency relief method, which is an encroachment and overdraft on the right to use resources for future generations, and is not sustainable in the long run. Even if we take into account the possibility of future technological advancements that could provide more efficient ways to utilize resources, this kind of overdraft behavior is still difficult to be justified morally. Even if it is not possible to stop the overdraft completely at present, at least the scale of it should be measured and a special fund (similar to the Alaska Permanent Fund) should be set aside for intergenerational compensation.

5. Horizontal compensation mechanism for ecological deficit

Vertical stock overdrafts alone cannot support long-term development in most regions, and more regions are relieving ecological pressures through interregional trade.

5.1. Basic ideas

Due to the trade among provinces, the products exported from a province need to consume its own resources, resulting in the weakening of ecological service functions. This impact corresponds to the value of ecological services, and how to allocate it reasonably is a key issue. Obviously, it is unreasonable to simply attribute the responsibility to either the place of production or the place of use. Therefore, this paper adopts the principle of shared responsibility to determine the local sharing ratio β_S and the foreign sharing ratio β_F:

$$\beta_S = 0.5 + 0.5\alpha \tag{11}$$

$$\beta_F = 0.5 - 0.5\alpha \tag{12}$$

Firstly, the producers and users of products share the responsibility for resource consumption equally, with each accounting for 50%. User is further divided into local and foreign user, with their share is determined by the parameter α. Once the parameter α is determined, each province can calculate what fraction of its ecological deficit is attributable to itself and what fraction should be compensated by other provinces.

The calculation of α requires the use of detailed data on the inflow and outflow of goods between provinces. However, China's official statistics do not provide systematic and continuous data on interprovincial trade. For this reason, drawing on the method of measuring the carbon emissions embodied in trade, the estimation is made using the inter-provincial input-output table. Currently, only inter-provincial input-output tables are available for 2002, 2007, 2012 and 2017 [5]. In order to maintain a consistent categorization of the input-output tables for each year, they are all combined into six sectors[6]. Then, distribute the total output of each province among all the provinces to obtain the matrix of output transfer ratios A. Any element α_{ij} represents the share of products flowing from province i to province j in the total output of province i, satisfying $\sum_j \alpha_{ij}=1$. For province i, the parameter α is α_{ii}, which is located on the main diagonal of matrix A.

According to equations (11) and (12), responsibility allocation ratio matrix B can be calculated from the output transfer ratio matrix A. Each element β_{ij} represents the proportion of the ecological deficit corresponding to the product produced in province i that should be shared by province j, which also satisfies $\sum_j \beta_{ij}=1$. In this way, we can obtain the matrix B for 2002, 2007, 2012 and 2017. Given that the provincial input-output structures are relatively stable in the short term, the matrix of intermediate years is extrapolated by linear interpolation. For the coefficient matrices of 1990-2001, the result of 2002 is used directly. For the data after 2018, the result of 2017 is used.

Finally, the matrix of ecological deficit value sharing amount is obtained by multiplying the corresponding value amount $ED \cdot b$ for any given year by the responsibility allocation ratio matrix B in the same year.

$$ED \cdot b = ED \cdot \frac{VES}{EC} = \frac{ED}{EC} \cdot VES = \frac{ed}{ec} \cdot VES \tag{13}$$

where ED is the total ecological deficit, b is the unit price of each type of ecological service, VES is the value of

[5] Shi Minjun et al. compiled a 30-province inter-district input-output table for 2002, and Liu Weidong et al. compiled a 30-province inter-district input-output table for 2007; the 31-province inter-district input-output tables for 2012 and 2017 were taken from CEAD.

[6] Agriculture, industry, construction, transportation and post and telecommunications and warehousing, wholesale and retail and accommodation and catering, and other services.

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ecological services, which is measured as described in section 5.2.

5.2. Measurement and analysis of the value of ecological service

5.2.1. Measurement methods and data

In view of the fact that the equivalent factor method is conducive to ensuring the comparability of ecological service value estimation results in the time and space dimensions, and it is convenient to reveal the correlation between ecological service value and GDP from a macroscopic point of view, this paper selects this method. This method treats natural resources such as agricultural land, forests and wetlands as relatively independent ecosystems. On the basis of distinguishing different types of ecosystem services, the value equivalents of various services of different types of ecosystems are constructed on the basis of quantifiable standards, and then multiplied with the physical area of the ecosystems and summed up to obtain the value of ecological services. The basic formula is:

$$VES_{it}^{k} = \sum_{j=1}^{m} e^{kj} \times D_t \times S_{it}^{k} = e^{k} \times D_t \times S_{it}^{k} \tag{14}$$

Where VES_{it}^{k} is the ecological service value of *k*-class natural resources in region *i* in period *t*. e^{kj} is the equivalent factor of ecological value for the *jth* service function[7] of *k*-class resources. D_t is the ecological value of 1 standardized equivalent factor in period *t* (national average). S_{it}^{k} is the land area of *k*-class resources in region *i.*

For the calculation of the standard unit equivalent factor value D_t, the economic value of equivalent factor of one ecological service value is approximately equal to 1/7 of the market value of the national average grain yield during the same period. This method is used as the base reference in this paper (marked as Method A). In order to eliminate the effect of price changes, the agricultural product price index is used to convert the data of each year to the price of 2000 in a uniform manner.

$$D_t = \frac{1}{7}\sum_{s=1}^{3}\frac{M_t^s P_t^s Q_t^s}{M_t} = \frac{1}{7}\sum_{s=1}^{3} w_t^s R_t^s \tag{15}$$

D_t is the ecological service value of 1 standard equivalent factor in China in year *t*. *s* is the grain types, taking rice, wheat and corn. M_t^s is the sown area of grain crops of class *s* in year *t* (hm^2). $M_t = \sum_s M_t^s$ is the total sown area (hm^2). $w_t^s = M_t^s / M_t$ is the share of sown area of grain crops of class *s*. $R_t^s = P_t^s Q_t^s$ is the output value per unit area of the grain crops of class *s* in year *t* (yuan).

In order to include information on all kinds of crops, the total annual value of crop production per unit area of cultivated land throughout the country is used instead, multiplied 1/7 as an alternative choice for the standard equivalence factor (denoted Method B). This method includes not only the other food crops but also various economic crops, so that the net returns per unit area are higher than those of the three major food crops. After repeated comparisons, the Method B is finally selected for the calculation of the standard unit equivalent factor value.

Table 6. Total value of ecological services in each province (unit: billion yuan)

Province	1990	2000	2019	Province	1990	2000	2019	Province	1990	2000	2019
Beijing	9.5	12.8	45.3	Anhui	139.9	209.8	642.8	Sichuan	924.4	1423.1	3685.7
Tianjin	20.1	29.1	55.2	Fujian	168.2	293.5	964.5	Guizhou	97.0	176.2	632.2
Hebei	171.3	240.7	596.8	Jiangxi	147.7	254.0	857.6	Yunnan	537.0	886.5	2668.4
Shanxi	105.6	152.1	457.2	Shandong	171.8	257.8	533.4	Tibet	1175.1	2010.1	5294.0
Inner Mongolia	1099.4	1722.8	4629.1	Henan	114.0	176.6	583.7	Shaanxi	218.7	300.2	815.1
Liaoning	165.3	251.6	692.7	Hubei	162.2	257.6	858.0	Gansu	282.5	422.3	1122.3
Jilin	371.2	560.7	1530.1	Hunan	159.7	269.8	863.0	Qinghai	727.4	1075.9	2574.8
Heilongjiang	899.1	1310.7	3534.4	Guangdong	174.1	305.6	834.4	Ningxia	30.0	42.6	107.8
Shanghai	34.0	50.9	58.6	Guangxi	185.1	319.7	1110.5	Xinjiang	666.7	1060.3	2804.4
Jiangsu	211.3	311.3	639.1	Hainan	40.4	67.3	249.8	Total	9386.9	14722.1	40284.8
Zhejiang	110.0	174.7	486.1	Chongqing	68.4	96.0	358.0				

Finally, the area of each type of resource S_{it}^{k} is taken from the China Statistical Yearbook, China Rural Statistical Yearbook and China Forestry Statistical Yearbook, specifically using the area of forests, grasslands, arable land, swamps and wetlands, and the area of waters.

5.2.2. Analysis of measurement results

On the basis of ESV_{it}^{k}, the total value of ecological services in region *i* and the whole country in period *t* are summed up at VES_{it} and VES_t, respectively.

Table 6 shows that the ecological service value of natural capital increased significantly in both the whole country and all provinces during the investigation period. The

[7] According to the classification of ecological service functions of the United Nations Millennium Ecosystem Assessment (MA), the total ecosystem value can be divided into four first-level indicators according to the source: regulatory services, support services, supply services and cultural services. The regulatory services include four functions: gas regulation, climate regulation, hydrological regulation and waste treatment; supporting services include two functions: soil formation and protection, biodiversity conservation; provisioning services include two functions: food production and raw material production; cultural services include 1 function of leisure and entertainment.

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difference in ecological service value between different provinces is huge: the total ecological service value of western provinces such as Tibet, Inner Mongolia, Heilongjiang, Sichuan, Xinjiang, Yunnan, and Qinghai is huge, with the highest of 5294.0 billion yuan in Tibet. While the value of ecological service of Beijing, Tianjin, and Shanghai is relatively low in 2019, the lowest is Beijing at 45.3 billion yuan. This huge difference mainly depends on the difference in natural resource endowment, but is also affected by the stage of economic development and land utilization.

Table 7. Value of the ecological deficit borne by each province in 1990 and 2019 (Unit: billion yuan)

province	1990				2019			
	income	expenditure	Net amount	Net/GDP	income	expenditure	Net amount	Net/GDP
Beijing	6.13	72.65	-66.52	-58.5%	103.36	862.91	-759.54	-41.3%
Tianjin	15.9	53.16	-37.26	-65.2%	70.86	437.09	-366.23	-37.6%
Hebei	69.53	145.26	-75.74	-54.6%	290.67	1125.77	-835.11	-39.2%
Shanxi	66.19	20.95	45.24	65.2%	1161.83	358.58	803.25	90.1%
Inner Mongolia	288.19	47.32	240.87	431.9%	4356.29	404.99	3951.3	300.3%
Liaoning	72.35	65.24	7.11	3.7%	728.25	558.26	169.99	8.1%
Jilin	103.86	48.03	55.83	81.9%	849.44	662.17	187.27	23.8%
Heilongjiang	88.13	76.57	11.56	8.6%	1287.69	547.31	740.38	56.6%
Shanghai	27.96	58.54	-30.58	-20.4%	342.27	707.44	-365.17	-13.7%
Jiangsu	44.28	107.53	-63.25	-27.5%	479.86	1529.75	-1049.89	-17.2%
Zhejiang	21.56	53.27	-31.71	-20.8%	697.16	1822.03	-1124.87	-29.0%
Anhui	22.55	36.6	-14.05	-13.3%	374.54	521	-146.46	-6.8%
Fujian	12.24	11.99	0.26	0.3%	440.13	259.11	181.03	6.7%
Jiangxi	12.76	22.17	-9.41	-12.1%	428.46	523.83	-95.37	-6.5%
Shandong	30.35	117.29	-86.94	-37.3%	189.11	650.39	-461.27	-9.8%
Henan	18.03	116.64	-98.61	-57.7%	266.73	1590.44	-1323.72	-39.6%
Hubei	21.11	27.33	-6.21	-4.9%	143.34	356.67	-213.33	-8.6%
Hunan	16.34	22.01	-5.67	-4.2%	223.51	415.49	-191.98	-7.7%
Guangdong	27.97	86.03	-58.05	-22.2%	535.6	1615.89	-1080.3	-15.2%
Guangxi	14.96	45.33	-30.37	-44.2%	113.6	359.99	-246.38	-21.0%
Hainan	0.47	8.11	-7.64	-47.0%	33.08	192.03	-158.96	-50.7%
Chongqing	20.43	26.07	-5.64	-9.1%	317.75	771.85	-454.1	-29.2%
Sichuan	174.94	251.95	-77.01	-53.0%	1057.19	2281.38	-1224.19	-43.5%
Guizhou	21.86	32.53	-10.67	-23.9%	667	608.36	58.64	7.5%
Yunnan	68.63	151.61	-82.98	-102.3%	457.68	1505.1	-1047.42	-82.6%
Tibet	566.87	221.21	345.66	8800.8%	4880.52	2175.26	2705.26	2886.3%
Shaanxi	38.54	77.69	-39.15	-56.5%	1162.72	819.36	343.36	26.6%
Gansu	65.9	77.5	-11.6	-28.2%	520.36	175.02	345.34	55.4%
Qinghai	113.14	25.57	87.57	738.5%	812.59	253.77	558.82	323.6%
Ningxia	7.08	16.88	-9.8	-76.9%	121.83	199.7	-77.87	-44.5%
Xinjiang	146.82	82.05	64.77	114.3%	2111.21	933.69	1177.52	150.2%

5.3. Measurement of horizontal compensation results

According to the above method, the ecological deficit compensation that should be borne by each province due to the flow of products can be calculated in 1990-2019. **Table 7** gives the results of the first and last two years. In most provinces, the due compensation is less than the payable compensation in most provinces. In 1990, only 9 resource-based provinces (e.g., Shanxi and Inner Mongolia are provinces with a large amount of coal resources, the three provinces in Northeast are provinces with a large amount of petroleum and forest resources, and Xinjiang is rich in oil and gas resources) should receive greater compensation than they pay, and the net ecological deficit compensation is positive. The remaining 22 provinces should compensate to the outside. In 2019, the number of provinces that should receive positive net ecological deficit compensation increased to 12, with Guizhou, Shaanxi and Gansu entering this group.

During the investigation period, the absolute amount of net ecological compensation increased rapidly with economic development. For this reason, it is compared with GDP to calculate the relative intensity. The results show that the ecological compensation Tibet, Qinghai, Inner Mongolia, and Xinjiang should receive from other provinces is significantly more than their own GDP, and the ratio has significantly decreased in 2019 compared to 1990. The ratio of ecological compensation that eastern provinces need to pay to their GDP mostly ranges from 10% to 50%, and most of them are on a decreasing trend, with only a few provinces experiencing an increase in the ratio (especially Chongqing).

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If provinces follow **Table 7** to compensate each other, the damage of ecological deficits can be compensated. However, the above measurements are too large, and their reliability heavily depends on the results of the ecological service value and parameter b. Therefore, the above discussion is quite valuable in the direction of countermeasures, but it is still far from becoming an implementable compensation plan. The fundamental difficulty is that the value of ecological services is a virtual appraisal value derived from academic research, and does not exist in actual economic transactions, so its value is not yet realizable.

Only when the value of ecological services is truly manifested can it be possible to implement ecological compensation based on it. Before that, the central finance can refer to relevant research results and make appropriate compensation for the transfer of ecological deficits corresponding to inter -provincial trade through transfer payments, so as to guide all provinces to adopt a greener and sustainable mode of development.

To sum up, vertical compensation is a contemporary responsibility to future generations, which needs to extract reserve from the current development and establish funds. Horizontal compensation is inter-provincial compensation, which needs to be implemented by means such as fiscal transfer payments. For Shanghai, its ecological deficit is large, and it mainly relies on inter-provincial trade to meet its demand at present, but there is no compensation mechanism so far. If the inter-provincial compensation is implemented later, then Shanghai solves its ecological deficit through horizontal transfer, and it does not create pressure and overdraw for its future population, so it is indeed not necessary to do vertical compensation additionally. In other words, each province should decide whether to compensate other provinces or future generations, or both, depending on their deficit resolution channels.

6. Conclusions, recommendations and outlook

6.1. Conclusions

The *ef* in China shows an upward trend from 1990 to 2019, and the pressure on resources and the environment continues to increase. The consumption degree of biological resources and energy in the northwest region is far higher than that in the southwest region. Although the overall *ec* is slowly increasing, there are significant differences among provinces and regions. The *ec* in developed regions such as Beijing, Shanghai, Jiangsu, Zhejiang and Guangdong decrease significantly. The *ef* of all provinces is larger than the *ec* during the investigation period, and the ecological deficits of the majority of provinces show an upward trend. China's footprint depth generally shows an upward trend and is greater than 1 during the investigation period, indicating that economic development always entails overexploitation of the ecological capital stock, especially in the developed eastern regions. The long-term accumulation of ecological liabilities causes a serious harm to China's sustainable development.

The vertical ecological compensation mechanism is to use in advance ecological services for future years through the overdraft of ecological capital stock. The accumulated overdraft years in each province are generally very high in 1990-2019, with an average of 87.3 years. Shanxi is overdrawn by 280.7 years, and Shanghai by an even higher 410.7 years. The lowest, Guangxi and Hainan, also have a cumulative overload of around 20 years. Given the lack of willingness and ability of provinces to compensate future generations, vertical compensation for ecological deficits is only a short-term emergency method and not sustainable in the long term.

The horizontal ecological compensation mechanism, which uses the implicit ecological value of inter-provincial product transfer to make spatial value compensation. The due compensation of most provinces is less than the payable compensation in 1990-2019. Only Tibet, Qinghai, Inner Mongolia, and Xinjiang should receive ecological compensation from other provinces significantly more than their own GDP, while the ratio of ecological compensation that eastern provinces need to pay to their GDP mostly ranges from 10% to 50%. Inter-provincial interaction compensation can eliminate the damage of ecological deficits, although the reliability of its measurements relies heavily on the value of ecological services and parameter b, it is valuable in the direction of countermeasures.

6.2. Policy recommendations

To alleviate the continuously increasing ecological and environmental pressure in China, the following countermeasures and suggestions are put forward.

Optimize the structure of land use. Strictly adhere to the red line of the total amount of arable land, increase the yields per unit area through technological progress and intensive production, and enhance the ecological carrying capacity of arable land to reduce the ecological deficit. Strictly controlling the total amount of construction land and improving the efficiency of land use are fundamental policy to promote construction of ecological civilization in China. Due to the limited land resources, it is imperative to take the path of conservation. Each province should establish a set of effective and distinctive land saving and utilizing models based on its actual conditions. Cities should tap into the existing stock of construction land and provide preferential policies for the development and construction projects on the land. Industrial parks should be established improve the intensive use of land and its benefits by centralizing the layout of construction land for industrial and mining enterprises. The principle of paid land use should be adhered to, and land use tax rate should be appropriately adjusted. In particular, the collection standard for newly requisitioned agricultural land should be increased to vigorously protect cultivated land. At the same time, local government departments in each province should strengthen the supervision of land use, establish a management database, and eliminate fraudulent and excessive use of land.

Promote the transformation and upgrading of industrial structure. China should formulate a national-level plan to

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cut production capacity in high-energy-consuming industries as soon as possible, and clarify the goals and tasks for each province to reduce the production capacity of high-energy-consuming enterprises. In particular, the economic development of provinces such as Shanxi and Inner Mongolia should strive to reduce the degree of dependence on natural resources. China should focus on developing strategic emerging industries such as new-generation information technology, biotechnology, high-end equipment, new energy and new materials, and promote the integration and development of emerging technologies such as the Internet, artificial intelligence, big data and 5G. Explore new mechanisms to reduce the ecological deficit by improving the modern industrial cluster system. Establish supporting systems such as upstream and downstream industrial chains, production and living services, public service system, and software and hardware environment, forming an intensive, compact, and scaled industrial collaboration system, thereby reducing energy consumption and emissions during transportation. Promote the sharing of energy resources and the joint governance of pollution among numerous enterprises within the agglomeration base. Meanwhile, technological innovation is the primary driving force for the development of industrial. It is necessary to accelerate technological progress and implant advanced technology and green management concepts into industries such as consumption and logistics, thereby reducing the EF.

Establish an ecological compensation mechanism. Ecological deficits can be resolved by drawing down special funds for vertical compensation, but the long-term strategy is to promote the realization of the value of ecological services in economic transactions. The central government can appropriately compensate for the transfer of ecological deficits corresponding to cross-provincial trade through transfer payments, in order to guide provinces to adopt greener and more sustainable development methods. Provinces should learn from the inter-provincial ecological compensation mechanism represented by the Xin'anjiang model, which highlights ecological priority and shared responsibility between upstream and downstream, and ensures effective implementation of the agreement by scientifically formulating assessment standards and strengthening dynamic monitoring. Through the vertical guidance of the central government (policies and funds) and the horizontal compensation among provinces, the incentive intensity can be improved in a multi-dimensional way, so as to ensure the reasonable distribution of ecological protection benefits. Moreover, compensation can also be made by combining diversified means such as cash, physical objects, or technology. For developed areas such as Jiangsu, Zhejiang, Shanghai, Beijing, and Guangdong, compensation can be made by providing advanced technological support to less developed areas such as Shanxi, Inner Mongolia, Tibet, Xinjiang, helping them train specialized technical and managerial personnel, or providing advanced equipment, etc., to help them reduce ecological pressure.

6.3. Research shortcomings and prospects

Firstly, due to data constraints, the calculation process of EF still has certain strong assumptions, which will have an impact on the change of the EF^d of the integrated land category. Secondly, the research on the way to resolve the ecological deficit is still a preliminary attempt, especially due to the constraints of the data of inter-provincial input-output tables, and lack of sufficient information to make a fine calculation of the sharing of compensation responsibilities under horizontal trade transfer. It must be recognized that the mechanism of inter-provincial ecological compensation is still far from mature. In view of the above issues, exploring reasonable and feasible treatment methods will constitute an important development direction for future research on ecological compensation: First, by obtaining data from multiple sources, gradually remove some assumptions in the calculation of EF. For example, distinguish the the yield factor for construction land from the yield factor for arable land. Second, with the continuous release of inter-provincial input-output tables, reduce the estimation of inter-provincial trade data in some years, so the calculation results of horizontal compensation are more refined, and thus continuously improve the inter-provincial compensation.

Declaration of Interest statement

Author Hongyuan Zhang is employed by Bank of Tianjin Co., Ltd. The remaining 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.

Research Data Policy and Data Availability Statements

The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

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