Postprint of Research on Land Carrying Capacity Index Based on Extended Three-Dimensional Ecological Footprint Model

Authors: Shen Wendong; Xu Hao; Liu Jianhua; Li Hang; Zhao Qing; Yu Shuixiao

Date: 2018-01-05T00:00:00+00:00

Abstract

Hebei Province, endowed with favorable geographical conditions, has experienced rapid economic development, yet faces challenges including resource shortages and ecological degradation that seriously impede sustainable development. To achieve sustainable development, maintaining its natural resource stock is essential. Therefore, quantifying the gap between residents' demand for natural resources and the supply capacity of nature in Hebei Province is of paramount importance. This study expands the value range of footprint depth in Niccolucci' s three-dimensional ecological footprint model from 1 to 0, employs a unified three-dimensional model framework to analyze ecological surplus states, achieves unified accounting of the degree of occupation of both resource flows and stocks in human production and consumption, and calculates the ecological footprint, deficit/surplus, and footprint depth for Hebei Province from 2002 to 2016. Building upon this, we introduce land pressure evaluation indices—including the agricultural product pressure index, water resource pressure index, carbon sink pressure index, construction pressure index, and land comprehensive burden index—to assess the overload status and degree of land use. The results demonstrate: 1) The per capita ecological footprint in Hebei Province exhibited a continuous upward trend from 2002 to 2016, while per capita ecologically productive land area remained relatively stable. 2) Hebei Province exhibits substantial footprint depth, particularly for water bodies and fossil fuel land; natural resources consumed by residents in production and daily life far surpass resource flows, resulting in substantial depletion of resource stocks; 3) The ecological deficit in Hebei Province is substantial, reaching 3.26 $hm^2 \cdot$ person ^{1} in 2016; 4) The agricultural product pressure index, water resource pressure index, carbon sink pressure index, and land comprehensive burden index all exceed 1, with pressure values for the water resource pressure index, carbon sink pressure index, and land comprehensive burden index all surpassing

10; Hebei Province faces severe land pressure, with residents' production and daily life imposing substantial burdens on various types of ecologically productive land. These four findings indicate that resource demand in Hebei Province far outstrips supply, seriously impeding sustainable development. To achieve sustainable development, Hebei Province must implement energy conservation and emission reductions, protect the environment, and minimize resource waste.

Full Text

Abstract

Hebei Province, endowed with favorable geographical conditions and rapid economic development, faces severe challenges including resource shortages and ecological degradation that significantly impede sustainable development. Maintaining natural capital stock is essential for achieving sustainability. Therefore, measuring the gap between residents' demand for natural resources and nature' s supply capacity is of critical importance. This study extends Niccolucci' s three-dimensional ecological footprint model by expanding the footprint depth range from 1 to 0, enabling unified analysis of ecological surplus/deficit states within a single three-dimensional framework. This extension achieves unified accounting of resource flow and stock consumption in human production and living activities. We calculated Hebei' s ecological footprint, deficit/surplus, and footprint depth from 2002 to 2016. Building upon these results, we introduced land pressure evaluation indices—including agricultural product pressure index, water resources pressure index, carbon sink pressure index, construction pressure index, and comprehensive land burden index—to determine land overload status and severity. The results show: (1) Per capita ecological footprint in Hebei increased continuously from 2002 to 2016, while per capita ecologically productive land area changed minimally. (2) Hebei' s footprint depth is substantial, particularly for water bodies and fossil fuel land, indicating that resource consumption far exceeds resource flows and causes massive depletion of resource stocks. (3) Hebei faces serious ecological deficit, reaching 3.26 hm^2 per capita in 2016. (4) All pressure indices exceed 1, with water resources, carbon sink, and comprehensive land burden indices all above 10, demonstrating severe land pressure and heavy burdens on various types of ecologically productive land. These findings indicate that resource demand far exceeds supply in Hebei Province, seriously hindering sustainable development. To achieve sustainability, Hebei must reduce emissions, protect the environment, and minimize resource waste.

Keywords: Hebei Province; Three-dimensional ecological footprint model; Footprint depth; Ecological carrying capacity; Land pressure index

Introduction

The foundation of contemporary socio-economic development lies in maintaining regional ecological health and abundant natural resources. As economies develop and living standards improve, demand for natural resources continues to grow. Overexploitation has led to desertification, air pollution, resource depletion, and other issues that hinder sustainable regional economic development. Consequently, achieving ecological sustainability is key to sustainable development [?]. Ecological sustainability refers to generating greater economic benefits with fewer resources while improving the ecological environment, and meeting ecosystem sustainability requirements in terms of time, space, and resource optimization—it constitutes the primary content and environmental foundation of sustainable development [?].

The ecological footprint method is commonly used to measure human demand for and nature' s supply of natural resources [?]. First proposed by Rees [?] in 1992 and further developed by Wackernagel [?] in 1996, this method calculates human resource utilization and natural resource supply, gaining widespread application and practice both domestically and internationally [?]. Niccolucci [?] introduced the three-dimensional ecological footprint model incorporating footprint depth and footprint size to characterize human use of resource flows and stocks. Fang and colleagues [?] first introduced this model to China and optimized it by adding capital flow occupancy rate and stock-flow utilization ratio indicators. However, previous research on the three-dimensional model failed to incorporate analysis of ecological surplus states into the unified three-dimensional framework.

Addressing this limitation, our study extends the original three-dimensional ecological footprint model by modifying the footprint depth value range, enabling calculation of resource flows using footprint depth and integrating surplus and deficit within a single model framework. This achieves unified accounting of resource flow and stock consumption. Using Hebei Province as a case study, we calculated ecological footprint, deficit/surplus, and footprint depth from 2002 to 2016. We further constructed a land pressure evaluation index system, calculating agricultural product pressure index, water resources pressure index, carbon sink pressure index, construction pressure index, and comprehensive land burden index to assess regional resource consumption and land carrying system overload.

1. Methodology

1.1 Three-Dimensional Ecological Footprint Model

Building upon the one-dimensional model, Wackernagel [?] introduced ecological surplus and deficit, developing the two-dimensional model with the following calculation formula:

$$EF = \sum_{i=1}^{n} \frac{c_i}{p_i} \times N = \sum_{i=1}^{n} a_i \times N$$
$$ED = EF - BC$$
$$ER = BC - EF$$

where i represents consumption product type, p_i is global average production capacity for product i, c_i is per capita consumption of product i, a_i is per capita biologically productive land area converted from product i, N is population, ef is per capita ecological footprint, EF is total ecological footprint, ED is ecological deficit, ER is ecological surplus, and BC is regionally available ecologically productive land area.

Based on the two-dimensional model, Niccolucci [?] added footprint depth and footprint size indicators, expanding the model to three dimensions for temporal analysis and explaining human production/living impacts on resource flows and stocks. While the two-dimensional model only represents natural resource flows, the three-dimensional model also represents natural resource stocks—resources consumed when flows cannot meet human demands.

Natural resource stocks are characterized by footprint depth. When regional ecologically productive land is smaller than ecological footprint, natural resource stocks are consumed, requiring footprint depth to represent stock consumption status. Footprint depth equals the ratio of ecological footprint to ecologically productive land. Footprint size represents consumption of resource flows, occurring when ecologically productive land exceeds ecological footprint, making footprint size equal to ecological footprint.

The two-dimensional model establishes the following relationship:

$$EF = BC + ED$$

where EF is ecological footprint, BC is regionally available ecologically productive land area, and ED is ecological deficit.

During model evolution, the following relationships exist:

If $EF - BC < 0$:

$$EF_{size} = EF$$

If $EF - BC > 0$:

$$EF_{depth} = \frac{EF}{BC}$$

where EF_{size} is footprint size and EF_{depth} is footprint depth.

1.2 Extended Three-Dimensional Model

1.2.1 Incorporating Natural Resource Flow Surplus Accounting Two-dimensional models simply use ecological surplus/deficit to describe whether human activities exceed regional supply capacity. Three-dimensional models calculate footprint size and depth to characterize resource flow consumption and stock overdraft. However, previous research focused only on stock overdraft calculations without examining resource flow surplus under surplus conditions.

Therefore, this study extends footprint depth in the three-dimensional model to enable calculation of resource flows, integrating surplus and deficit within a unified framework.

Previous models used footprint size to represent ecological footprint during surplus periods, failing to incorporate ecological surplus and deficit within a single three-dimensional framework. After extension, the footprint size indicator is no longer used.

The extended three-dimensional model is as follows:

When $0 \leq EF_{depth} < 1$ (e.g., point M):

$$EF_{depth,M} = \frac{EF_M}{BC}$$

When $0 \leq EF_{depth} < 1$, resource flows have surplus without stock consumption, and ecological footprint is in surplus. Footprint depth represents resource flow consumption. The extended model enables temporal calculation of ecological surplus magnitude, achieving three-dimensional characterization of natural resource flow usage states. Calculations proceed as:

$$ER_M = BC - EF_M \times EF_{depth,M}$$

where ER_M represents ecological surplus magnitude at point M, indicating remaining resource flow quantity after human consumption.

When $EF_{depth} = 1$ (e.g., point N):

$$EF_N = BC$$

At this point, resource consumption equals resource flow, representing a critical point with neither surplus nor deficit.

When $EF_{depth} > 1$ (e.g., point P):

$$EF_{depth,P} = \frac{EF_P}{BC}$$

where $EF_{depth,P}$ is footprint depth at point P and EF_P is ecological footprint at point P. When $EF_{depth} > 1$, resource stocks are consumed, meaning footprint depth characterizes stock consumption degree.

Ecological deficit is calculated as:

$$ED_P = EF_P \times (EF_{depth,P} - 1)$$

where ED_P is ecological deficit at point P. Niccolucci’ s original model lacked three-dimensional expression under ecological surplus conditions. This study extends $EF_{depth} \geq 1$ to $EF_{depth} \geq 0$, incorporating surplus states into footprint depth. By calculating flow occupation under surplus and stock usage under deficit, the two states are unified, achieving computational integration of resource flows and stocks.

1.2.2 Handling Ecological Deficits and Surpluses Among Land Types

Previous calculations converted resource consumption into six productive land types: cropland, grassland, forestland, built-up land, fossil fuel land, and water bodies. After adjusting and summing these areas, total ecological footprint was obtained without considering functional and productivity differences and substitution relationships among land types, creating significant errors [?]. This study calculates footprint depth and ecological surplus/deficit for each land type to analyze resource supply-demand relationships and guide regional land structure research. Equivalence factors adjust each land use type to unify functional dimensions, and after summation, Hebei' s ecological footprint and footprint depth are calculated. This approach yields more accurate results, functionally integrating various land types within the region.

2. Land Pressure Index Construction

Based on the extended model, we constructed land pressure indices for agricultural products, water resources, construction, carbon sinks, and a comprehensive land burden index. These indices evaluate burdens on different land types from human activities and refine the land comprehensive carrying capacity index system [?].

2.1 Agricultural Product Pressure Index

Agricultural product pressure originates from regional residents' demand for agricultural products [?]. Agricultural pressure can be expressed as the product of per capita agricultural demand and population:

$$G_p = G_a \times P$$

where G_p is regional agricultural pressure, G_a is per capita annual agricultural demand, and P is total population.

Agricultural production capacity equals the product of cropland area and productivity:

$$G_a = P_a \times A$$

where G_a is regional agricultural production capacity, P_a is cropland output, and A is total cropland area.

The agricultural pressure index is inversely proportional to production capacity and directly proportional to pressure:

$$I_{food} = \frac{G_p}{G_a} = \frac{EF_{arable}}{BC_{arable}}$$

where I_{food} is agricultural pressure index (also cropland footprint depth), EF_{arable} is cropland ecological footprint, and BC_{arable} is regional cropland area.

2.2 Water Resources Pressure Index

Water resources pressure is calculated based on water demand for production and living [?]. Regional water pressure equals per capita water demand multiplied by total population:

$$W_p = W_a \times P$$

where W_p is water pressure and W_a is per capita water demand.

Water carrying capacity is represented by W_s. The water pressure index is directly proportional to W_p and inversely proportional to W_s:

$$I_{water} = \frac{W_p}{W_s} = \frac{EF_{sea}}{BC_{sea}}$$

where I_{water} is water pressure index (water body footprint depth), S is maximum water provision per unit area, EF_{sea} is water consumption ecological footprint, and BC_{sea} is total water area.

2.3 Construction Pressure Index

Regional construction pressure is directly proportional to built-up land demand. The construction pressure index is:

$$I_{built-up} = \frac{CD}{CS} = \frac{EF_{built-up}}{BC_{built-up}}$$

where $I_{built-up}$ is construction pressure index (built-up land footprint depth), CD is construction land demand, CS is construction land supply, $EF_{built-up}$ is built-up land ecological footprint, and $BC_{built-up}$ is built-up land area.

2.4 Carbon Sink Pressure Index

Carbon sink pressure refers to the amount of CO from fossil fuel combustion that nature must assimilate [?]. Carbon sink pressure is proportional to CO emissions:

$$C_p = E_a \times P$$

where C_p is carbon sink pressure and E_a is per capita CO emissions.

CO assimilation is primarily completed by forestland, cropland, and grassland, so carbon sink capacity is proportional to their areas. Regional carbon sink capacity is characterized by CO assimilation quantity:

$$I_{sink} = \frac{C_p}{A} = \frac{EF_{fossil}}{BC_{forest}}$$

where I_{sink} is carbon sink pressure index (fossil energy land footprint depth), A is CO assimilation capacity of forestland, cropland, and grassland, EF_{fossil} is fossil fuel consumption ecological footprint, and BC_{forest} is total area of forestland, cropland, and grassland.

2.5 Comprehensive Land Pressure Index

The comprehensive land pressure index quantifies agricultural product consumption, water consumption, construction demand, and CO emissions using ecologically productive land area. Equivalence factors balance productivity differences among land types, and after summation, regional population ecological footprint is obtained. Footprint depth represents the comprehensive land pressure index:

$$I_{comprehensive} = \frac{EF}{BC}$$

where $I_{comprehensive}$ is comprehensive land pressure index (regional footprint depth), EF is regional ecological footprint, and BC is regionally available ecologically productive land area.

2.6 Data Sources

The extended three-dimensional ecological footprint model includes two consumption categories: biological resources and energy. Biological resource consumption focuses on daily food consumption such as agricultural products, animal products, aquatic products, fruits, and timber, using world average yield standards from the Food and Agriculture Organization. Energy consumption includes coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, natural gas, heat, and electricity. Electricity and heat consumption are converted to standard coal using coefficients from the *China Energy Statistical Yearbook 2010*, then to built-up land area using global average standard coal energy footprint. Other fossil energy consumption is converted to fossil fuel land using global average calorific value standards per unit fossil fuel production land area.

Biological and energy consumption data are primarily from the *Hebei Statistical Yearbook* (2002–2016). Equivalence factors use values published in WWF' s *Living Planet Report 2008* (2005 data), and yield factors use values calculated by Liu et al. [**?**] for Chinese land types in 2001. Hebei' s ecologically productive land area is based on land use change survey data from 2003–2017.

3. Results

3.1 Changes in Hebei' s Ecological Footprint

Hebei' s ecological footprint by land type (Table 1) grew continuously from 2002 to 2016, reaching a maximum of 3.46 hm² per capita in 2016. Per capita area across six land types remained around 0.22 hm² with minimal variation (Figure 1 [Figure 1: see original paper]). The increasing ecological footprint indicates rising natural resource consumption, while stable per capita land area places an unbearable burden on Hebei' s ecosystem, undermining sustainable development.

By land type, per capita ecological footprints for cropland and water bodies remained around 0.50 hm² and 0.98 hm² respectively, with small increases. Grassland per capita footprint was 0.43 hm² in 2016, a 0.03 hm² decrease from 2002. Minimal changes in these three land types suggest Hebei 基本实现粮食自给自足. Forestland provides fruits and timber while absorbing CO from fossil fuel combustion. In our calculations, all forestland is assumed to have both functions, with ecological footprint remaining around 0.10 hm². Fossil fuel land per capita footprint reached 2.40 hm² in 2016, a 0.62 hm² increase from 2002, indicating extremely rapid growth in fossil fuel consumption far exceeding biological assimilation capacity and increasing pressure on forestland to absorb CO . Due to rapid population growth and housing demand, built-up land ecological footprint increased from 0.001 hm² to 0.005 hm² per capita, though remaining small because strict planning controls protect cropland and ecological redlines.

By city, land area by type changed minimally while ecological footprints increased. Zhangjiakou showed slow growth, with per capita footprint below 1.00 hm², indicating underutilization of natural resources. Baoding, Cangzhou, Chengde, Qinhuangdao, and Xingtai showed slow increases of 1.10–1.50 hm² per capita. Hengshui, Shijiazhuang, and Tangshan had large and rapidly growing footprints, reaching 5.29 hm², 5.92 hm², and 7.43 hm² per capita respectively in 2016—increases of 2.41 hm², 2.50 hm², and 3.67 hm² from 2002. This rapid growth stems from economic development heavily reliant on natural resource consumption, threatening sustainability.

3.2 Changes in Hebei' s Footprint Depth

Overall, Hebei' s footprint depth (Table 2 , Table 3) is substantial, increasing from 12.40 in 2002 to 17.29 in 2016. This indicates that over the 14-year period, natural resource consumption far exceeded resource flows, with stock consumption increasing annually, creating an extremely serious ecological burden.

By land type, all categories except forestland have footprint depths exceeding 1, indicating deficit status. Cropland footprint depth increased by 1.32 during 2002–2016, reaching 6.58 in 2016. This means achieving food self-sufficiency requires 6.58 times current cropland area under existing cultivation technology. Hebei has extensive forestland in the Yanshan and Taihang Mountains, providing strong timber supply, so forestland footprint depth remained below 1 but increased gradually. Despite extensive Bashang grasslands providing strong livestock capacity, supporting 75.25 million residents resulted in grassland footprint depth reaching 7.67 in 2016. Rapid economic development and high energy consumption created large fossil fuel land footprint depth of 24.36 in 2016. Although Hebei borders the Bohai Sea, water shortages and small water area create high water body footprint depth, though decreasing annually. Built-up land footprint depth remains at 1 because we equated built-up land in ecological footprint with actual built-up land area. Hebei' s average footprint depth around 30 places enormous burden on land resources.

By city, all cities except Zhangjiakou had ecological footprint depths exceeding 1, with values reaching over 46. Baoding, Cangzhou, Handan, Langfang, and Zhangjiakou showed rapid growth rates of 234.40%, 251.24%, 313.61%, 228.49%, and 403.85% respectively. Qinhuangdao showed slower growth due to tourism development, afforestation, and elimination of high-pollution enterprises. Five other cities grew at 110%–190%. Shijiazhuang, Tangshan, Hengshui, and Handan, with rapid industrial development and high fossil fuel land footprint depth, had average footprint depths exceeding 30. Zhangjiakou' s footprint depth remained below 1 before 2016 due to its large land area and sparse population with underutilized productive land.

3.3 Analysis of Ecological Surplus and Deficit in Hebei

Using footprint depth results and formulas (11) and (15), we calculated Hebei' s ecological surplus/deficit for 2002–2016. Results show Hebei is in ecological deficit, increasing annually to a maximum of 3.26 hm^2 per capita in 2016—a 25.59% increase from 2.59 hm^2 in 2002. This indicates serious obstacles to sustainable development, with resource demand far exceeding supply, requiring massive resource imports and environmental degradation to maintain rapid development.

By land type, all categories except forestland and built-up land are in deficit, increasing annually. Fossil fuel land deficit reached 4.60 hm^2 per capita in 2016, primarily due to energy-intensive economic development. By city, all cities except Zhangjiakou are in serious ecological deficit. In 2002, Baoding, Cangzhou, Chengde, Handan, Langfang, and Qinhuangdao had deficits of 0.50–1.50 hm² per capita, while Hengshui, Shijiazhuang, and Xingtai had 1.50–3.50 hm² deficits, and Tangshan had 3.57 hm². By 2016, only Zhangjiakou remained below 1.50 hm², with all other cities exceeding 1.50 hm². Tangshan, Shijiazhuang, and Hengshui were most severe, exceeding 5.10 hm² per capita, due to rapid urbanization, high consumption, and large populations with limited land.

3.4 Analysis of Hebei' s Land Pressure Indices

Hebei' s agricultural product, water resources, construction, carbon sink, and comprehensive land pressure indices for 2002–2016 are shown in Table 6 .

The agricultural product pressure index increased annually, indicating growing pressure on Hebei's cropland. Agricultural consumption exceeds cropland capacity by 5.26–6.58 times, due to Hebei' s topography with limited cropland area and large population with severe consumption pressure. Reducing this index requires strict cropland protection policies and high-yield crop cultivation.

Despite bordering the Bohai Sea, Hebei has small productive water area and large population, creating high water pressure. The water resources pressure index decreased overall from a 2006 peak of 58.29 to 34.22 in 2016, mainly due to water management and diversion projects increasing available resources.

Carbon sink pressure index increased annually from 13.26 in 2002 to 24.36 in 2016, driven by rising fossil energy consumption and CO emissions [?].

Comprehensive land pressure index increased from 12.40 in 2002 to 17.29 in 2016, indicating continuously growing land pressure and severe challenges to sustainable development. Achieving sustainability requires reducing ecological pressure, protecting cropland, reducing emissions, efficiently utilizing resources, and decreasing CO emissions.

4. Conclusion and Discussion

Based on the extended three-dimensional ecological footprint model, this study calculated Hebei' s ecological footprint, surplus/deficit, and footprint depth from 2002 to 2016, measuring natural consumption burdens on land. Through agricultural product, carbon sink, water resources, comprehensive land, and construction pressure indices, we evaluated Hebei' s ecological carrying capacity. Key findings:

(1) During 2002–2016, Hebei' s ecological footprint increased annually while ecologically productive land area changed minimally, causing ecological deficit to increase yearly, reaching 3.46 hm² per capita in 2016. By land type, cropland and water body areas rose slightly but remained basically stable. By city, ecologically productive land area changed little while ecological footprints increased across all cities.

(2) Hebei' s per capita footprint depth ranged from 12.40 to 17.29, with consumption far exceeding supply. By land type, all categories except forestland had footprint depths exceeding 1, consuming resource stocks. By city, footprint depth increased annually, all exceeding 1. The smallest was Zhangjiakou at 1.31 in 2016; the largest was Shijiazhuang at 46.02, indicating uneven development and severe stock depletion.

(3) Hebei is in ecological deficit, increasing annually to 3.26 hm^2 per capita in 2016, a 25.59% increase from 2002. Fossil fuel land and cropland deficits were largest, reaching -0.43 hm^2 and 4.60 hm^2 per capita respectively in 2016. By city, all except Zhangjiakou had serious, rapidly growing deficits. Shijiazhuang and Tangshan were most severe at 5.80 hm^2 and 7.27 hm^2 per capita respectively in 2016.

(4) All pressure indices exceed 1, with cropland, forestland, and water bodies severely overloaded. Comprehensive pressure index grew from 12.40 in 2002 to 17.29 in 2016, indicating heavy burdens on all ecologically productive land from human activities.

4.2 Discussion

This study extends the three-dimensional ecological footprint model by using footprint depth to characterize resource flow consumption, eliminating original model limitations. Unlike comprehensive indicator system approaches, the extended model uses ecologically productive land area to quantify ecological pressure and environmental support capacity. Land area enables spatial comparison, while footprint depth adds temporal dimension to land carrying status in the three-dimensional model, more vividly reflecting relationships between natural resource consumption and land ecological supply.

Due to limited vegetation carbon sequestration data, this study assumes all forestland, grassland, and cropland have CO assimilation functions. In built-up land footprint depth calculations, equating built-up land in ecological footprint with actual built-up land area yields a constant depth of 1, but we retain the construction pressure index to allow for future methodological improvements. Additionally, the extended model remains closed, not considering inter-regional resource trade and energy flows. Therefore, exploring cooperative relationships in inter-regional land pressure under open systems represents an important direction for future research improvement.

Note: Figure translations are in progress. See original paper for figures.

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