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Natural capital utilization on an international tourism island based on a three-dimensional ecological footprint model: A case study of Hainan Province, China

Hongwei Dong[a,b], Peng Li[a,b], Zhiming Feng[a,b,*], Yanzhao Yang[a,b], Zhen You[a,b], Qiang Li[c]

[a] *Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China*
[b] *College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China*
[c] *Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China*

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ABSTRACT

Natural capital is a limited and irreplaceable factor for human welfare and sustainability. Natural capital includes natural capital flow and natural capital stock. When natural capital flow cannot meet the needs of regional development, it begins to consume natural capital stock. Therefore, the assessment of the current utilization status of natural capital flows and stocks is not only the basis for regional ecological construction evaluation but also an important indicator of the effectiveness of regional sustainable development strategies. This study uses the three-dimensional ecological footprint model to systematically and comprehensively evaluate the utilization status of natural capital flows and stocks in Hainan Province from 2005 to 2016. The driving factors behind changes in the natural capital stock are revealed using a partial least squares method. Our results indicate the following. (1) The per capita ecological footprint of Hainan Province is increasing at an annual rate of 3.87%, and the per capita ecological deficit is increasing at an annual rate of 5.85%. The ecological footprints are mainly composed of cropland and forest land and the account composition is dominated by the biological and energy accounts; (2) The growth of water body natural capital flow promotes the total natural capital flow consumption of Hainan Province from 2005 to 2016 with an annual average of 0.41%. The natural capital flow consumption is mainly in the north, northeast and southwestern cities and counties, and the growth rate of natural capital flow consumption is greatest in the central mountainous region; (3) The consumption of total natural capital stock is growing at an average annual rate of 4.49%, from a value of 2.97 times the sustainable resource consumption of Hainan Province in 2005, increasing to a factor of 4.81 times in 2016. The natural capital stock consumption is mainly in the north and northeast in terms of quantity and growth rate; (4) The secondary industries, the year-end resident population, the total energy consumption and the total investment in fixed assets are the natural capital stock consumption of Hainan Province. These findings can provide a scientific reference for the formulation of Hainan's economic development and environmental protection policies to promote the coordinated and sustainable development of social, economic and environmental aspects of Hainan Province.

1. Introduction

Since the publication of *Our Common Future* in 1987, sustainable development has evolved from theory to practice. Eco-economics has reached a consensus on sustainable development, noting that the minimum level of sustainable development is such that the natural capital stock that does not decrease (Pearce et al., 1989; Pezzey, 1990; Costanza and Daly, 1992). Natural capital is a general term for the natural resources and ecological services provided by the ecosystem. Natural capital is divided into two parts: natural capital flow and natural capital stock. Natural capital flow refers to the inter-annual supply of renewable resource flows and their ecological services. Additionally, natural capital stock refers to the cumulative reserve of non-renewable resource flows, which is consumed only when the natural capital flow is insufficient (Daly, 1996). Therefore, ways to measure the utilization of natural capital objectively and accurately are particularly important. Over the past several decades, some indicators have been suggested to achieve reliable natural capital accounting, the important of which is

* Corresponding author at: Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China.
E-mail addresses: donghw.17b@igsnrr.ac.cn (H. Dong), fengzm@igsnrr.ac.cn (Z. Feng).

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the ecological footprint theory (Wackernagel et al., 1999). Since the development of this theory, the ecological footprint approach has been widely used to assess the use of natural capital.

Based on the classic ecological footprint model, Borucke et al. (2013) improved the natural capital accounting method, analysed the natural capital footprint of more than 200 countries, and found that most countries have experienced ecological deficits, indicating that these countries are in an unsustainable state. Li et al. (2016) analysed the dynamic changes in the ecological footprint of arid regions in northern China from 1990 to 2010 on a time-series basis. The study also showed that the region has become unsustainable, although the traditional ecological footprint model recognizes the importance of natural capital in sustainable development. However, this model cannot distinguish the mutual relationship between capital flow and capital stock, and the accumulation and unsustainable status of ecological overdraft is difficult to reflect temporally (Mancini et al., 2017). Therefore, the three-dimensional ecological footprint (3D EF) model was proposed by Niccolucci et al. (2009, 2011). These researchers introduced the ecological footprint depth (EF depth) and ecological footprint size (EF size) measurements to characterize the levels of natural capital stocks and flows, building on previous ecological footprint research methods. Peng et al. (2015) incorporated this model into a 3E (ecology-equity-efficiency) framework for assessing the use of natural capital in Beijing. The model was recently adopted by Yang and Hu (2018), who monitored the changes in the EF size and depth of north Shaanxi in China.

Compared with the traditional ecological footprint model, the three-dimensional ecological footprint model can compare and track the use of natural capital stocks and flows, but it remains largely ignored by researchers in the sustainability debate, which may be due to two reasons. First, the existing three-dimensional ecological footprint model overestimates the size of the footprint and underestimates its depth at the regional scale (Niccolucci et al., 2011). Accurate ecological deficit results are the premise for and key to calculating the footprint depth. For a single category, the ecological deficit equals the difference between a category's ecological footprint and its bio-capacity. However, a region usually contains multiple types of land. If the regional ecological deficit is still subtracted from the sum of the ecological footprints of various regions and the bio-capacity, it may underestimate the true state of the ecological deficit to a certain extent. The reason for this underestimation is that the ecological deficit of certain land types (such as cultivated land) is partially offset by the ecological surplus of other land types (such as grassland), resulting in a smaller regional ecological deficit and regional footprint. Therefore, the calculation of regional ecological deficits must be based on detailed regional ecological deficit data, rather than on the final regional cumulative data. Second, the lack of standardized detailed calculation formulas makes practical applications difficult (Mancini et al., 2017; Fang et al., 2018). Therefore, Fang (2015) and Fang et al. (2018) improved the existing three-dimensional ecological footprint model and established a universal formula for the size and depth of the footprint on the land use types and regional scales to more accurately calculate the regional ecological deficit. This work not only makes its calculation result scientific and persuasive but also easy to operate and apply. It is thus a non-negligible part of sustainable-development research, with a view to providing a scientific basis for regional sustainable development and providing a scientific reference for the formulation of sustainable development policies.

The establishment of Hainan Province and a special economic zone in 1988 provided an opportunity for the development of Hainan, a backward border island. With the collapse of the property market in 1998, Hainan Province took the lead in proposing to build an ecological province, with eco-tourism and tropical agriculture as important industrial pillars. In 2009, the State Council issued the "Several Opinions on Promoting the Construction and Development of Hainan International Tourism Island", which elevated the construction of Hainan International Tourism Island to a national strategy. In 2017, the 7th Party Congress of Hainan Province once again emphasized the need to speed up the construction of an international tourist island and give play to the "three advantages" (the best ecological environment in the country, the largest special economic zone in the country and the only provincial international tourism centre in the country), that is, to speed up the construction of new Hainan. Ulucak and Lin (2017) showed that policy implementation such as government policies to encourage or discourage the use of fossil fuels has an important impact on ecological footprint changes and that the ecological footprint is also an important consideration in policy formulation. Now, Hainan Province faces the dual pressure of developing its economy while protecting the ecology and will inevitably face the problems of ecological damage, environmental pollution and resource consumption. Therefore, this study uses the three-dimensional ecological footprint model to systematically and comprehensively evaluate the utilization status of natural capital flows and stocks in Hainan Province from 2005 to 2016. The driving factors behind changes in the capital stock are revealed using a partial least squares method. These findings can provide a scientific reference for the formulation of Hainan's economic development and environmental protection policies to promote the coordinated and sustainable development of social, economic and environmental aspects of Hainan Province.

2. Methods and data

2.1. Study area

Hainan Province is located in the southernmost part of China. The north is delimited from the Qiongzhou Strait and Guangdong Province, and the northern borders by the Beibu Gulf. The east and south connect the South China Sea to the Philippines, Brunei, Indonesia and Malaysia. This province's administrative areas include Hainan Island; the Xisha, Zhongsha and Nansha Islands; and their reefs. This province is the largest in China with an area of approximately 2 million square kilometres. The land (including Hainan Island and Xisha, Zhongsha, and Nansha Islands) has an area of 35,400 square kilometres (including Hainan Island with an area of 33,900 square kilometres). Hainan Province has a tropical monsoon climate. The distribution of the soil from low to high in Hainan Island is a complete vertical soil band in the red soil of the red brick-red soil, the loess red soil and the loess-mountain shrub. As the country's major strategic deployment, Hainan International Tourism Island is officially launched in 2010. This deployment will initially establish Hainan as a world-class island leisure resort in 2020, making it an open island, a green island, an island of civilization and an island of harmony. Since the human activities in Hainan Province are mainly concentrated on Hainan Island, the study area in this paper mainly concentrates on Hainan Island and its surrounding sea areas, totalling approximately 23,712.9 square kilometres and strongly disturbed by human activities (as in Fig. 1).

2.2. Methods

2.2.1. Calculating ecological footprint and biocapacity

The ecological footprint account in this study is divided into four parts: the biological account, the built-up land account, the energy account and the pollutant account. To maintain the consistency of the ecological footprint and the components of the biocapacity land category, this study integrated the land for construction into the calculation of cultivated land and incorporated land for pollutant discharge accounts into forest land, water areas, and cultivated land, which were used respectively to absorb sulfur dioxide, wastewater and the accumulation of solid waste (Yang et al., 2018).

In calculating land use types and individual accounts for the ecological footprints of production and waste generation the following formula is used (Lin et al., 2018):

Fig. 1. Location of the study area.

$$EFP = \frac{P}{YW} * EQF * IYF \quad (1)$$

where EF_P is the ecological footprint associated with a product or waste (gha), P is the amount of product extracted or waste generated (t yr^{-1}), Y_W is the world-average yield for product extraction or waste absorption (t wha^{-1} yr^{-1}), EQF is the equivalence factor for a given land use type (gha wha^{-1}), IYF is the intertemporal yield factor of a given land use type.

The single *biocap* worksheet uses data on area, yield factors, and equivalence factors to calculate the bio-capacity of each land type. The calculation of bio-capacity follows (Lin et al., 2018):

$$BC = A * YF * IYF * EQF \quad (2)$$

where BC is the bio-capacity of a given land use type (gha), A is the area of a given land use type within a country (nha), and YF is the yield factor of a given land use type within a country (wha nha^{-1}), IYF is the intertemporal Yield factor of a given land use type for that year, EQF is the equivalence factor for a given land use type (gha wha^{-1}), and BC is calculated by subtracting 13.4% of the local biodiversity (Venetoulis and Talberth, 2005).

2.2.2. Ecological footprint size and depth

Fang (2015) and Fang et al. (2018) improved the existing three-dimensional ecological footprint model and established a universal formula for the size and depth of the footprint on the land use types and regional scales to more accurately calculate the regional ecological deficit, following the formulas:

$$EF_{size,i} = \min\{EF_i, BC_i\} \quad (3)$$

$$EF_{depth,i} = 1 + \max\{EF_i - BC_i, 0\}/BC_i \quad (4)$$

$$EF_{size,region} = \sum_{i=1}^{n} \min\{EF_i, BC_i\} \quad (5)$$

$$EF_{depth,region} = 1 + \sum_{i=1}^{n} \max\{EF_i - BC_i, 0\}/\sum_{i=1}^{n} BC_i \quad (6)$$

where $EF_{size,i}$ is the EF size of the natural capital flow for the i-th land use type (gha), $EF_{depth,i}$ is the EF depth of the natural capital stock for the i-th land use type, $EF_{size,region}$ is the region's EF size of natural capital flow (gha), $EF_{depth,region}$ is the region's EF depth of natural capital stock, EF_i is the ecological footprint for the i-th land use type (gha), and BC_i is the bio-capacity for the i-th land use type (gha).

2.2.3. Regional natural capital flows remain

The existing three-dimensional ecological footprint model is characterized by the introduction of footprint size and depth to characterize the consumption of natural capital flows and capital stocks. It focuses on measuring the overdraft of natural capital stocks in the context of ecological deficits, and does not involve the surplus of natural capital flow (Niccolucci et al., 2009). Therefore, this study built a natural capital flow surplus calculation formula based on regional land use types and scaled to accurately quantify the surplus of regional natural capital flow, calculated as follows:

$$EFremain, i = 1 - \{\min[EFi, BCi]/BCi\} \quad (7)$$

where $EF_{remain,i}$ is the remaining natural capital flow for the i-th land use type (gha).

2.3. Data sources

The research period for this study was from 2005 to 2016. Because there is no detailed trade data, when calculating the ecological footprints at the provincial and sub-provincial levels, it is more reasonable to use the yield of agricultural, forest, animal and aquatic products instead of consumption to calculate the occupation of an ecologically productive land area. Detailed data sources and descriptions are shown in Table 1.

3. Results

3.1. Biological capacity and ecological footprint analysis

Using formulas (1) and (2), the per capita ecological footprint (ef), the per capita ecological deficit (ed) and the per capita biological capacity (bc) were obtained from Hainan Province in 2005–2016 (as shown in Fig. 2). Specifically, the ef is increasing at an annual rate of 3.87%, from 3.43 gha/person in 2005 to 5.21 gha/person in 2016. The bc is slowly decreasing year by year at an annual rate of −0.93%, from 1.25 gha/person in 2005 to 1.12 gha/person in 2016. The ed is increasing at an annual rate of 5.85%, increasing from −2.19 gha/person in 2005 to −4.09 gha/person in 2016.

From the perspective of the type of land use within the ecological footprint of Hainan Province, cropland accounts for the largest

Table 1
Indicators and data sources and instruction.

Items	Indicators	Data Sources
Biological account	Agricultural products:rice, wheat, sweet potato, cassava, taro, corn, sorghum, beans, pork and eggs Forest products:banana, pineapple, mango, lychee, longan, rubber, coconut, pepper, betel nut, and tea leaf Grass products:beef, lamb, milk, poultry Aquatic products:seawater and freshwater	《Hainan Statistical Yearbook》 (2006–2017)
Energy account	The consumption of oil, coal and natural gas	《Hainan Statistical Yearbook》 (2006–2017)
Built-up land account	Urban village, industrial, mining, and transportation land	《Hainan Statistical Yearbook》 (2006–2017)
Pollution account	Domestic sewage and industrial wastewater discharge, SO_2 emissions and solid waste accumulation	《Hainan Environmental Statistics Annual Report》(2006–2017)
Land use	Land use area	Land Resources Data of the Ministry of Natural Resources (2009–2016)and 《Hainan Marine Functional Division》(2012)
Pollutant degradation	SO_2 (88.65 kg/hm^2), sewage (365 t/hm^2) and solid waste (10.9 × 104 t/hm^2)	《Improvement of Ecological Footprint Model Based on Freshwater Resource Account and Pollution Accounts》 (Duan et al., 2015)
Equivalence factor	cultivated land (2.52), grassland (0.46), woodland (1.29), water areas (0.37), fossil energy land (1.29), construction land (2.52)	《Working Guidebook to the National Footprint Accounts》 (Lin et al., 2018)
Yield factor	cultivated land (1.5), grassland (3.8), woodland (1.68), water areas (3.8), fossil energy land (1.68), construction land (2.5)	《The calculation of productivity factor for ecological footprints in China: A methodological note》 (Liu et al.,2014)
Population Scale, economic, social and resource consumption	year-end resident population, GDP, total investment in fixed assets and total energy consumption et al	《Hainan Statistical Yearbook》 (2006–2017)

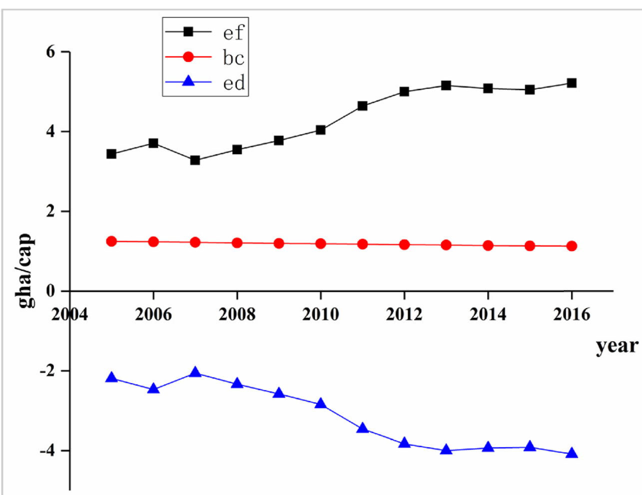

Fig. 2. Trend of ef, ed and bc from 2005 to 2016 in Hainan Province.

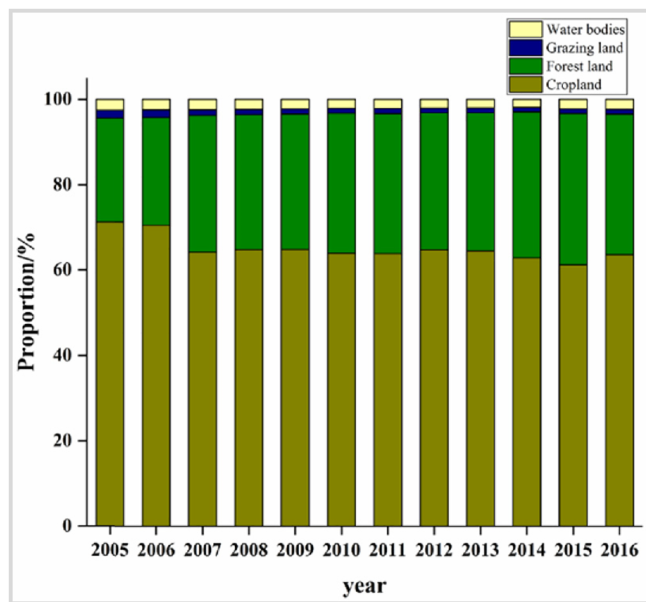

Fig. 3. Proportion of the four land types in the total ecological footprint.

proportion, followed by forest land and water bodies with the smallest proportion being grazing land (as shown in Fig. 3). Specifically, in 2016, the ecological footprint of cropland accounted for 63.61% of Hainan's total footprint, forest land accounted for 32.9%, water bodies accounted for 2.29%, and grazing land accounted for 1.2%. The proportion of the various land use types in the ecological footprints from 2005 to 2016 has not changed much. Except for the value of 70% for cropland in 2005 and 2006, the proportion of cropland in other years is between 61% and 65%. Except for the proportion of forest land in 2005 and 2006 being below 30%, the proportion of forest land in other years is between 31% and 36%. The proportion of grazing land footprints in 2005–2016 declined overall but did not change much. The proportion of the footprint of water bodies has decreased from 2.55% in 2005 to 1.85% in 2014, but the proportion has rebounded in the last two years, which is related to the increase in marine aquaculture in Hainan Province in the past two years.

From the perspective of the internal account structure of Hainan's ecological footprint, the largest proportion consists of the biological account, followed by the energy account, and again the pollution account. The smallest proportion is the built-up land account. This corresponds to the internal territorial composition of the total footprint of the study area, as the biological account and energy account, containing the largest proportions, correspond to the cropland and forest land (as Fig. 4). Specifically, in 2016, the biological account was 66.24% of Hainan's total footprint and the energy account was 30.87%, the pollution account was 1.45%, and the built-up land account was 1.44%. The proportion of the biological account as a whole has fluctuated and declined, but the change is not large. The proportion of the energy account has increased year by year since 2005, peaking in 2015 and falling in 2016, which is related to energy-saving and emission-reduction measures in the study area. It must be specifically stated that the proportion of the pollution account is declining year by year, which is inseparable from the concept of ecological islands and the measures to build an ecological civilization that the research area has always advocated.

3.2. Natural capital occupation analysis

3.2.1. Analysis of regional ecological footprint size

Fig. 5 is a trend chart showing the overall ecological footprint size

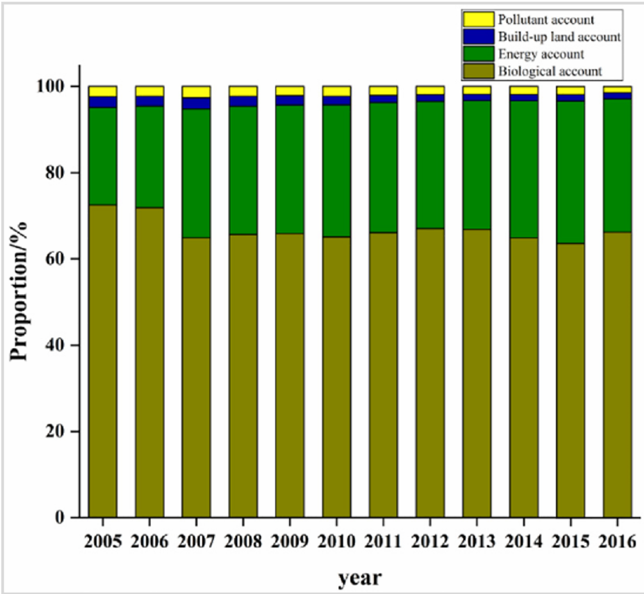

Fig. 4. Proportion of the four accounts in the total ecological footprint.

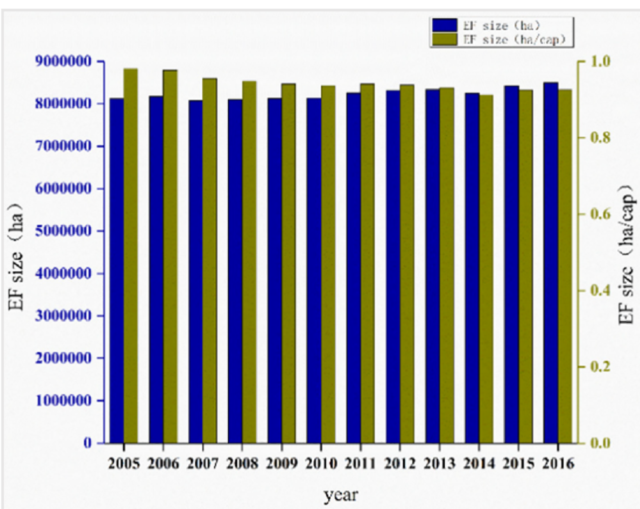

Fig. 5. Trend of the overall ecological footprint size in Hainan Province.

time series in the study area. On the whole, the size of the footprint of Hainan Province has been increasing slowly from 2005 to 2016, while the size of the per capita footprint has been slowly fluctuating. This shows that although the use of natural capital flows in Hainan Province has increased slightly, the population growth rate is faster. Therefore, the per capita use of natural capital flows has decreased. Specifically, the use of natural capital flows in Hainan Province increased at an average annual rate of 0.41%, from 8,122,382.55 gha in 2005 to 8,495,521.48 gha in 2016. The per capita natural capital flow use declined at an average annual rate of −0.52% from 0.98 gha/person in 2005 to 0.93 gha/person in 2016.

Fig. 6 is a schematic diagram showing the sequence changes of the ecological footprint of each county in the study area at three points in 2005, 2010 and 2016. In terms of total consumption, natural capital flow consumption exceeds 600,000 gha in Zhangzhou, Haikou and Wenchang. Consumption below 200,000 gha is mainly concentrated in Wuzhishan, Qiongzhong, Baoting and Baishan Counties and other central mountainous areas of Hainan Province. The consumption of other counties is concentrated between 200,000 and 600,000 gha. In terms of consumption growth, the average annual growth rate of natural capital flow consumption increased by more than 3% in the central mountainous areas of Hainan Province such as Qiongzhong, Baoting, Wuzhishan, Baisha and Ledong. Suichang, Zhangzhou and Lingshui are among the areas between 1% and 3% and the average annual growth rate of capital flow consumption of all other counties is below 1%.

3.2.2. Analysis of regional ecological footprint depth

Fig. 7 is a trend diagram showing the time series of the overall ecological footprint depth in the study area. The depth of the ecological footprint in the research period of Hainan Province is greater than 1, indicating that the natural capital flow in the region can no longer meet the needs of regional development and consumes a large amount of natural capital stock. In 2016, Hainan's ecological footprint depth was 4.81, which means that 4.81 times the existing area is needed to support the resource consumption of Hainan Province. The resource pressure is very high. The depth of Hainan's ecological footprint has grown at an average annual rate of 4.49% from 2.97 in 2005 to 4.81 in 2016. This shows that the utilization of natural capital in Hainan Province is both natural and capital-based, and the regional sustainability is deteriorating (Fang, 2014). Specifically, the growth of natural capital stock consumption in Hainan Province can be divided into three stages. The first stage is 2005–2007, with the total amount of stock consumption in this stage fluctuating greatly. The second stage is 2007–2013 during which the total consumption of the stock increased significantly. The third stage was 2013–2016; the total amount of stock consumption in this period changed more smoothly, which is related to the focus in Hainan Province on the construction of an ecological civilization in recent years.

Fig. 8 is a schematic diagram showing the sequence of changes in the ecological footprint depth of each county in the study area at the three time points of 2005, 2010 and 2016. Judging from the total consumption of natural capital stock, counties with a depth of more than 6 in 2016 include Chenzhou, Haikou, Qionghai, Ding'an and Chengmai. Areas with a depth of less than 2 are located in Wuzhishan and Qiongzhong counties, which are located in the central mountainous area of Hainan Province. The ecological footprint depth of the remaining counties is between 2 and 6. In terms of the growth rate of natural capital stock consumption, the areas with an average annual growth rate of more than 6% include Zhangzhou, Chengmai, Changjiang, Baoting and Ding'an. The areas with an average annual growth rate of less than 2% include Lingao, Wenchang, Haikou, Wuzhishan and Ledong, and the average annual growth rate of the remaining counties is between 2% and 6%.

3.2.3. Analysis of remaining regional natural capital flows

Using formula (5), you can obtain the percentage of natural capital flows remaining in each land use type of the study area (as Fig. 9). From Fig. 5, we know that the total consumption of natural capital flows in Hainan Province is slowly increasing from 2005 to 2016, but it is unclear for exactly what type of land uses the natural capital flows are growing. It can be seen from Fig. 9 that there is no surplus of capital flow for cropland, forest land and grazing land in Hainan Province from 2005 to 2016, all of which are consumed; however, the supply of water body capital flow is increasing and the remaining amount is still relatively large. Overall, the percentage of the remaining amount of water body capital flow in Hainan Province decreased from 75.17% in 2005 to 62.38% in 2016 at an annual rate of −1.68%.

3.3. Factors driving changes in the EF depth of the natural capital stock

The ecological footprint reflects the region's degree of sustainable development and utilization of resources. It has a direct or indirect relationship with the region's social and economic development. In this research, the natural capital flow used has changed little, and the main reason for the increase in the ecological footprint is the increase in the utilization of natural capital stock. To explore the driving factors of the use of natural capital stock in Hainan Province, a PLS model of the EF

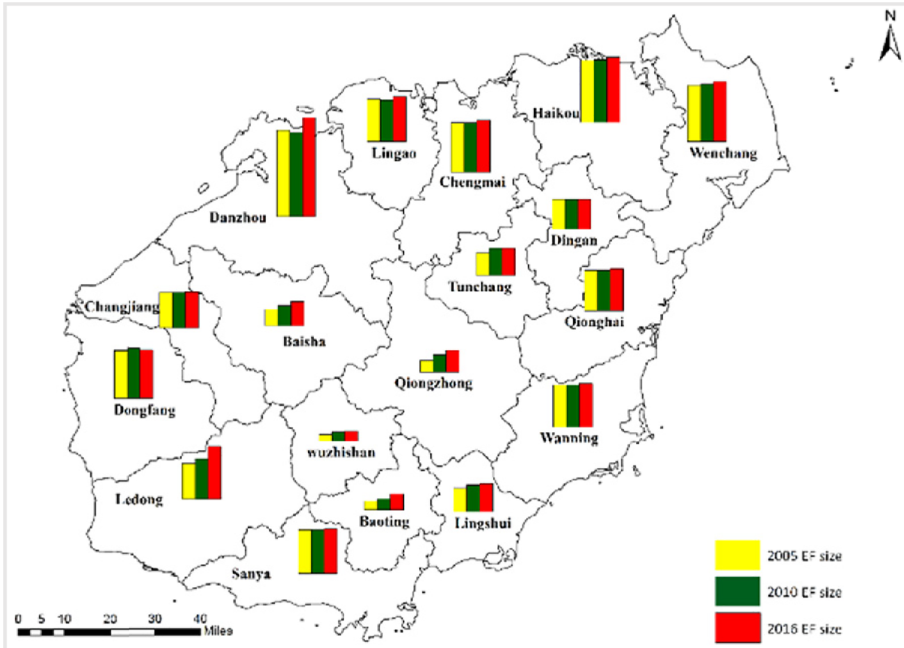

Fig. 6. Trend of the ecological footprint size of each county in Hainan Province.

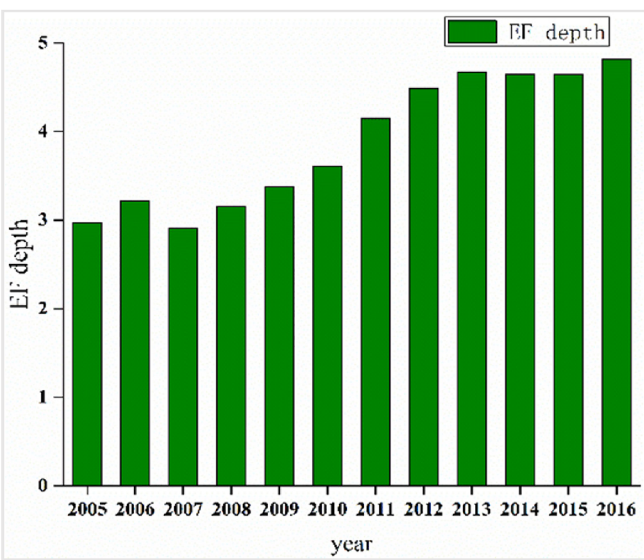

Fig. 7. Trend of the overall ecological footprint depth in Hainan Province.

depth of the natural capital stock was built. Referring to the indicators that already affect the ecological footprint (Lai et al., 2006; Fang et al., 2009; Jia, 2015), the EF depth of the natural capital stock was selected as the dependent variable Y, and 11 indexes of four major indicators—including population scale, economic indicators, social consumption indicators and resource consumption—were taken as the independent variables (as shown in Table 2).

Based on the results, the variable importance-in-projection (VIP) scores were obtained (as shown in Fig. 10). A VIP value greater than 1 indicates particularly important influencing factors. In this study, secondary industry (X3), year-end resident population (X1), total energy consumption (X11) and total investment in fixed assets (X6) are particularly important. A VIP value of greater than 0.8 and less than 1 indicates generally important factors. The remaining general important factors were ranked in descending order as follows: per capita disposable income of rural residents (X8), primary industry (X2), GDP (X5), total retail sales of consumer goods (X7), annual per capita disposable income of urban residents (X9), tertiary industry (X4) and annual per capita energy consumption of households (X10).

The PLS model of regional EF depth data in Hainan Province obtained the following:

$$Y = 162.272 - 0.203X_1 + 0.469X_2 + 0.465X_3 + 0.452X_4 - 0.467X_5 + 0.003X_6 + 0.031X_7 - 0.003X_8 + 0.001X_9 - 0.005X_{10} + 0.005X_{11}$$

In terms of the population scale, the year-end resident population is the second factor affecting the growth in the depth of Hainan's ecological footprint. The population is growing, the demand for products and services is increasing, and this demand is more dependent on the consumption of natural resources. Therefore, it has become an important driving force for the growth in the depth of the regional ecological footprint. In terms of economic factors, the output value of the secondary industry is the most important factor for the depth growth of Hainan's ecological footprint, followed by fixed asset investment. In comparison, the tertiary industry has little effect on the consumption of natural capital stock in Hainan Province. In addition, the continuous increase in the total energy consumption is also an important factor leading to the continued growth of Hainan's ecological footprint. All of these fully explain that to reduce the consumption of natural capital stock in Hainan Province, we should accelerate the transformation of the economic growth mode, optimize the economic structure, and promote regional sustainable development. As far as social consumption is concerned, the per capita disposable income of rural residents has become an important factor affecting the growth in the depth of Hainan's ecological footprint. This is related to the increasing investment of rural residents in agriculture in recent years and the continuous increase in agricultural output.

4. Discussion

4.1. Ecological stress status of the Hainan Province

Similar to China as a whole, the Hainan Province was in an ecological overshoot status during the study period, and its ecological deficit had an increasing trend on a yearly basis. Since 1961, the per capita ecological footprint in China has been increasing at a steady rate, reaching an ecological overspending status in 1969. In the 1990s, the increase of the per capita ecological footprint accelerated. Since the

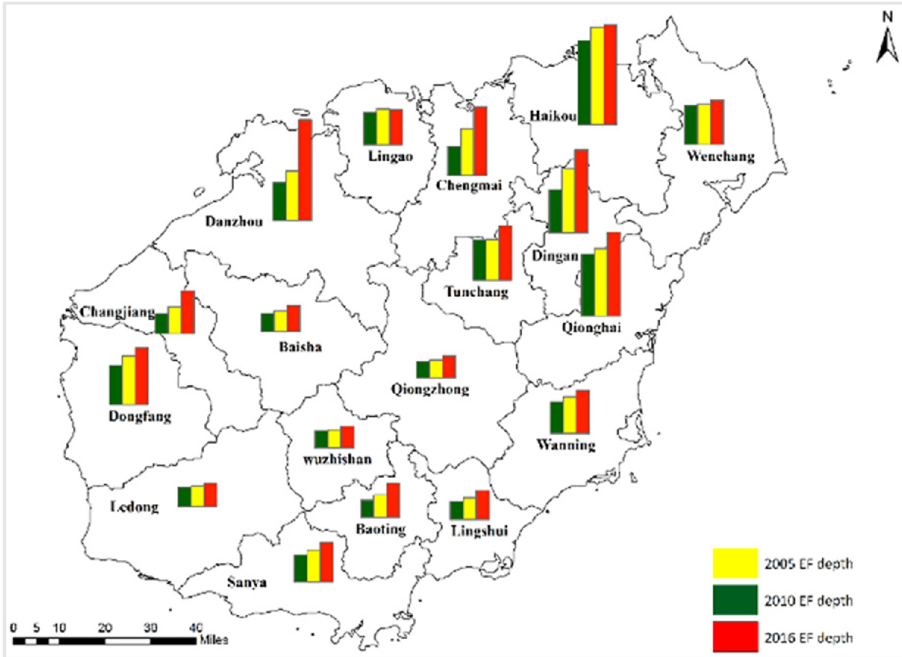

Fig. 8. Trend of the ecological footprint depth of each county in Hainan Province.

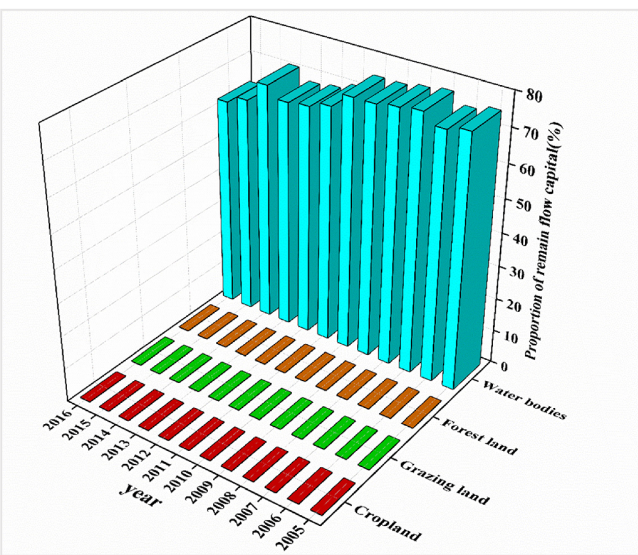

Fig. 9. Proportion of the four land use types natural capital flows remain in Hainan Province.

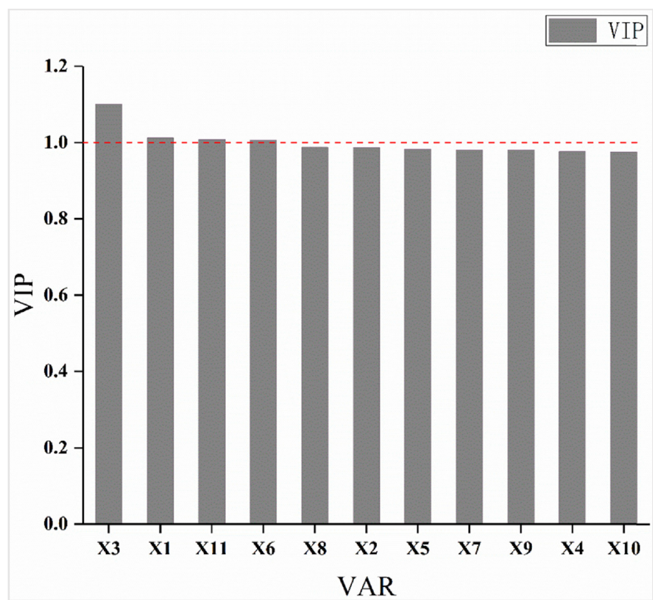

Fig. 10. Variable importance in PLS model's projection output graph of the EF depth of the natural capital stock in Hainan Province.

Table 2
Driving factors behind the EF depth of the natural capital stock change.

Aspects	Driving Factors	Independent Variable
Population Scale	year-end resident population (10,000 persons)	X1
Economic Indicators	primary industry (100 million yuan)	X2
	secondary industry (100 million yuan)	X3
	tertiary industry (100 million yuan)	X4
	GDP (100 million yuan)	X5
	total investment in fixed assets (100 million yuan)	X6
Social Consumption	total retail sales of consumer goods (100 million yuan)	X7
	annual per capita disposable income of rural residents (yuan)	X8
	annual per capita disposable income of urban residents (yuan)	X9
Resource Consumption	annual per capita energy consumption of households (kgsce)	X10
	total energy consumption (10,000 tce)	X11

beginning of the 21st century, China has realized a robust economic growth, accompanied by the rapid increase of the per capita ecological footprint and the further deterioration of the ecological overspending (WWF, 2015). This study modified the conventional ecological footprint model by including the consideration of pollution; hence, in order to increase persuasion and scientificity, it is necessary to take the study that has modified the conventional ecological footprint model as an example for clarification. In 2015, the per capita ecological footprint in the Hainan Province was 5.05 hm^2/cap, a value that was lower than the northern Shaanxi Province (5.299 hm^2/cap) (Yang et al., 2018). In 2016, the ecological footprint per capita in China was 1.34 times higher than that of the Hainan Province, thanks to the decision of the Hainan Province in 1999 to be an "Ecological Province" (Yang and Yang, 2019). In 2009, the construction of an "international tourism island" in the Hainan Province was uplifted at the level of national strategy; by insisting on the development strategy of ecological province and giving priority to the environment, the Hainan Province aimed to turn itself into a national eco-civilization construction demonstration area and a four seasons garden. As a consequence, the quality of the environment in the Hainan Province is higher than the national average.

From the perspective of the internal structure of the ecological footprint, the proportion of the cropland footprint in the ecological footprint in Hainan is the largest, followed by that of the energy footprint. Before the 1980s, the cropland footprint had always been the largest component of the ecological footprint in China. After that, the energy footprint replaced it as the part with the largest scale and the fastest growth in China's Ecological Footprint (WWF, 2015). This is explained by the fact that, as the national tropical characteristic industry base, the Hainan Province has given full play to its advantages of holding tropical resources, striving to develop a modern tropical agriculture. So far, an efficient tropical agricultural system has been created in Hainan. The reliance on external supply for about 80% of crops, livestock, and poultry before the construction of the province has been decreased, and today the rate of the agricultural output value to the provincial economic growth is the highest at national level.

4.2. Status quo of regional sustainable development in Hainan

Achieving sustainable development is the consensus of global development in the 21st century and one of the major challenges that the global need to address in the 21st century (Guerry et al., 2015). Ecological economy holds that regional sustainable development means that the natural capital stock cannot be reduced (Costanza and Daly, 1992). This study accurately calculated the utilization of the natural capital flow and the consumption of natural capital stock during 2005–2016 in the Hainan Province, according to the established, three-dimensional ecological footprint calculation formula from land use types to regions.

As far as the utilization of the natural capital flow is concerned, the natural capital flows of cropland, forest land, and grassland in Hainan have been entirely utilized, and the increment of total natural capital flow in the province mainly comes from the increasing of the water bodies flow. According to the General Planning of Hainan Province (Spatial Class 2015–2030), the agricultural and fishery areas in Hainan include agricultural reclamation areas, fishery infrastructure areas, aquiculture areas, breeding areas, fishing areas, and fisheries genetic resources protection areas. By 2020, the agricultural and fishery areas in Hainan will account for 56.98% of the nearshore functional areas, thereby presenting a great production potential.

In terms of the consumption of natural capital stock, the ecological footprint depth in Hainan was 4.81 in 2016; this means that the regional development was in an unsustainable status. Seen from the internal structure of natural capital stock consumption, the cropland had the largest natural capital stock consumption, followed by forest land. However, the natural capital stock consumption of forest land in Hainan showed the highest growth rate during 2005–2016, mainly manifested as the accelerated growth of the energy footprint. Therefore, the main reasons that led to the increase of capital stock consumption in Hainan included the output value of secondary industry, the residential population at year-end, the total energy consumption, the total fixed asset investments. It should be clarified that since 2013, the overall growth rate of natural capital stock consumption in Hainan has slowed down, indicating that the construction of eco-civilization (social-ecological sustainability) in the province has been fruitful.

4.3. Policy suggestions for the regional sustainable development of Hainan

The harmony between economic development and environmental protection has always been a dilemma for national and regional development. Based on the results of this study, we propose the following policy suggestions to achieve a sustainable and healthy development of the Hainan Province.

First, agricultural development: Adhere to the principle of agriculture as the foundation of social economic development in Hainan, and build tropical agriculture as the "trump card" of Hainan's economy. Agriculture should be considered as an important industrial support for provincial rural development, and to increase the income of farmers. Finally, the transformation and upgrading of agricultural industry in an all-round way should be promoted, establishing a resource-saving and environmentally-friendly industrial system with unique characteristics and outstanding advantages, and constructing a bigger and stronger tropical agriculture.

Secondly, social economic development: Insist on scientific development and green rise, seize the opportunity to construct an international tourism island, significantly improve the quality of the services and the globalization level, vigorously develop a modern industry led by tourism, and complete the transformation and upgrading of the industrial structure. The construction of an ecological province should be finalized, insisting on a civilized development path characterized by production and development, affluent existence, and good ecology, and creating a new, modern construction pattern of harmonious development between human and nature.

Thirdly, the implementation of the strategy of constructing a strong marine province: Optimize the marine spatial pattern, enhance the protection of the marine environment and its resources, and establish a marine industrial system led by marine tourism and supported by the marine oil and gas chemical industry, the marine transportation industry, and the marine fishery. Moreover, there is the fundamental need to guarantee the needs of fishermen's production and living, as well as a modern fishery development, and effectively protect important fishery waters, aquatic wildlife, and fisheries genetic resources. As a result, a fishery development system should be established, in which both the fishing capacity and the fishing production can basically adapt to the affordability of fishery resources.

4.4. Uncertainties and limitations

There are some uncertainties and limitations in this study. Further research work should focus on the following three aspects to improve the scientific value of the research. First of all, although the three-dimensional ecological footprint concept takes a significant step ahead from the traditional ecological footprint model, its representation of natural capital is still insufficient. For example, the threshold for natural capital stock depletion caused by humans remains unclear (Steffen et al., 2015). Second, natural capital includes our common stock of natural resources (water, minerals, land, etc.) and ecosystems (Daly, 1996). Therefore, when characterizing human consumption of natural capital, it should be combined with environmental footprints such as water footprint, land footprint, and material footprint for comprehensive quantification (Steinmann et al., 2017). Third, the biological account of this study is based on the accounting of production data. However, the main drawback of this approach is that it does not take into account the environmental pressures embodied in imports, thus creating incentives to shift environmental pressures outside the province (Ali, 2017). Besides, this study adopts a top-down approach, and all the data used are from the Hainan Statistical Yearbook and the Hainan Environmental Statistical Yearbook. When calculating the ecological footprint of the county-level scale, the accuracy of the data is insufficient, and it should be corrected in combination with the field survey data.

5. Conclusions

Natural capital is a limiting and irreplaceable factor for human welfare and sustainability. Therefore, the assessment of the current utilization status of natural capital flows and stocks is not only the basis for regional ecological construction evaluation but also an important indicator of the effectiveness of regional sustainable development strategies. This study uses the three-dimensional ecological footprint model to systematically and comprehensively evaluate the utilization status of natural capital flows and stocks in Hainan Province from 2005 to 2016. The driving factors behind changes in the capital stock are revealed using a partial least squares method. Our results indicate the following:

(1) From 2005 to 2016, Hainan Province has been facing severe ecological pressure. Specifically, the per capita ecological footprint is increasing at an annual rate of 3.87%, and the per capita ecological capacity is slowly decreasing at an annual rate of −0.93%. The per capita ecological deficit is increasing at an annual rate of 5.85%. From the perspective of the internal land use types of ecological footprints in Hainan Province, cropland accounts for the largest proportion, followed by forest land and water bodies. The smallest proportion is grazing land. From the perspective of the internal account structure of Hainan's ecological footprint, the largest proportion consists of the biological account, followed by the energy account, and again the pollution account. The smallest proportion is the built-up land account. It is necessary to emphasize that the proportion of the energy account declined in 2016, and the proportion of pollution account has been declining year by year. This is in line with the implementation of energy-saving and emission reduction measures in the research area in recent years and the consistently advocated construction of ecological islands to build an ecological and civilized international tourism.

(2) From 2005 to 2016, the total consumption of natural capital flow in Hainan Province increased at an average annual growth rate of 0.41%. The increase was mainly from the water bodies and the space for growth remained large. The rest of the capital flow of land-use types has been fully consumed. Since the rate of increase in capital flow is lower than the growth rate of the population, the per capita capital flow consumption is slowly fluctuating at an average annual rate of −0.52%. Judging from the various counties in Hainan Province, the top three counties in terms of total capital flow consumption are Zhangzhou, Haikou and Wenchang, but the average annual growth rate of counties with the highest total consumption of capital flow is comparatively low. The counties ranked lower in total capital flow consumption are mainly concentrated in the central mountainous areas of Hainan Province such as Wuzhishan, Qiongzhong, Baoting and Baisha. However, the average annual growth rate of these regions is relatively high, and their average annual growth rate continues to be more than 3%.

(3) The consumption of natural capital stock in Hainan Province continued to grow at an average annual rate of 4.49% from 2005 to 2016. The consumption of total capital stock is growing at an average annual rate of 4.49%, from a value of 2.97 times the sustainable resource consumption of Hainan Province in 2005, increasing to a factor of 4.81 times in 2016. Resource pressures are high and regional sustainability is deteriorating. However, since 2013, the growth rate of capital stock consumption has eased, indicating that pressure on resources in Hainan Province has begun to improve in recent years. From the perspective of counties, the counties with the highest capital stock consumption are mainly concentrated in the northern and north-eastern parts of Hainan Province, such as Zhangzhou, Haikou, Qionghai, Ding'an and Chengmaiy. The growth rate of consumption is also high, indicating that resource pressures in these counties continue to grow, and regional sustainability continues to deteriorate rapidly. The counties with lower capital stock consumption are concentrated in Wuzhishan, Qiongzhong and Baisha, and the growth rate of capital stock consumption of these counties is also low, indicating that although the resource pressure in these areas has increased, it is overall more moderate.

(4) The ecological footprint reflects the extent of sustainable development and resource utilization in the region, and it has a direct or indirect relationship with the social and economic development of the region. The continuous growth of Hainan's ecological footprint is mainly due to the increasing consumption of natural capital stocks. The study found that the increase in the consumption of natural capital stock in Hainan Province is mainly due to the output value of the secondary industry, the year-end resident population, the total energy consumption and total investment in fixed assets. Therefore, in view of the fact that Hainan Province is still an underdeveloped area as a whole, in order to promote its healthy and sustainable economic development, it is necessary to speed up the transformation of the existing industrial structure and reduce the excessive dependence of economic development on real estate and other industries. Taking advantage of the construction of an international tourism island is an opportunity to give full play to Hainan's location and resource advantages and to promote the transformation and upgrading of the tourism industry, thereby increasing the proportion of the service industry in Hainan's GDP. Efforts will be made to carry out practical energy-saving and emission-reduction measures, vigorously develop new industries with low energy consumption and low emissions, and accelerate the elimination of backward production capacity. These efforts will promote low-carbon development of transportation, give priority to the development of renewable-energy vehicles, take the lead in the popularization of Haikou and Sanya, and build a green transportation demonstration province.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.04.031.

References

Ali, Y., 2017. Carbon, water and land use accounting: consumption vs production perspectives. Renewable Sustainable Energy Rev. 67, 921–934.
Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., et al., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: the national footprint accounts' underlying methodology and framework. Ecol. Indic. 24, 518–553.
Costanza, R., Daly, H.E., 1992. Natural capital and sustainable development. Conserv. Biol. 6 (1), 37–46.
Daly, H.E., 1996. Beyond Growth: the Economics of Sustainable Development. Beacon Press, Boston, pp. 25–76.
Duan, J., Kang, M.Y., Jiang, Y., 2015. Improvement of ecological footprint model based on freshwater resource account and pollution accounts. J. Nat. Resour. 27 (6),

953–962 in Chinese.
Fang, K., 2014. Changes in the spatial distribution of natural capital useamong G20 countries from 1999 to 2008. Resour. Sci. 36 (4), 0793–0800 in Chinese.
Fang, K., 2015. Assessing the natural capital use of eleven nations: an application of a revised three-dimensional model of ecological footprint. Acta Ecol. Sinica 35 (11), 3766–3777 in Chinese.
Fang, Jiande, Yang, Yang, Ye, Di, Zhou, Xie, Chen, Xiaoyan, 2009. Analysis on dynamical character of ecological footprint and its driving factors in Chongqing city. Ecol. Environ. Sci. 18 (4), 1337–1342 in Chinese.
Fang, K., Zhang, Q.F., Yu, H.J., Wang, Y.T., Dong, L., Shi, L., 2018. Sustainability of the use of natural capital in a city: measuring the size and depth of urban ecological and water footprints. Sci. Total Environ. 631–632 (2018), 476–484.
Guerry, A.D., Polasky, S., Lubchenco, J., et al., 2015. Natural capital and ecosystem services informing decisions: from promise to practice. Proc. Natl. Acad. Sci. 112 (24), 7348–7355.
Jia, Junsong, 2015. Hierarchical partial least squares (Hi_PLS) model analysis of the driving factors of Henan's Ecological Footprint (EF) and its development strategy. Acta Ecol. Sinica 31 (8), 2188–2195 in Chinese.
Lai, Li, Huang, Xian-jin, Liu, Wei-liang, 2006. Socio-Economic Driving Model of Regional Ecological Footprint: A Case of Jiangsu Province from 1995 to 2003. Resour. Sci. 28 (1), 14–18 in Chinese.
Li, J.W., Liu, Z.F., He, C.Y., Tu, W., Sun, Z.X., 2016. Are the drylands in northern China sustainable? a perspective from ecological footprint dynamics from 1990 to 2010. Sci. Total Environ. 553, 223–231.
Lin, D., Hanscom, L., Martindill, J., Borucke, M., Cohen, L., Galli, A., Lazarus, E., Zokai, G., Iha, K., Eaton, D., Wackernagel, M., 2018. Working Guidebook to the National Footprint Accounts. Global Footprint Network, Oakland.
Liu, M.C., Li, W.H., Xie, G.D., 2014. The calculation of productivity factor for ecological footprints in China: a methodological note. Ecol. Indic. 38 (2014), 124–129.
Mancini, M.S., Galli, A., Niccolucci, V., Lin, D., Hanscom, L., Wackernagel, M., Bastianoni, S., Marchettini, N., 2017. Stocks and flows of natural capital: implications for ecological footprint. Ecol. Indic. 77, 123–128.
Niccolucci, V., Bastianoni, S., Tiezzi, E.B.P., Wackernagel, M., Marchettini, N., 2009. How deep is the footprint? A 3D representation. Ecol. Modell. 220, 2819–2823.
Niccolucci, V., Galli, A., Reed, A., Neri, E., Wackernagel, M., Bastianoni, S., 2011. Towards a 3D national ecological footprint geography. Ecol. Modell. 222, 2939–2944.
Pearce, D., Barbier, E., Markandya, A., 1989. Blueprint for a green economy: a report for the UK department of the environment. Earthscan Publ., Lond., pp. 43–44.
Peng, J., Du, Y.Y., Ma, J., Liu, Z.W., Liu, Y.X., Wei, H., 2015. Sustainability evaluation of natural capital utilization based on 3D EF model: a case study in Beijing City, China. Ecol. Indic. 58, 254–266.
Pezzey, J., 1990. Economic Analysis of Sustainable Growth and Sustainable Development. World Bank, Washington, DC.
Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 1259855.
Steinmann, Z.J.N., Schipper, A.M., Hauck, M., Giljum, S., Wernet, G., Huijbregts, M.A.J., 2017. Resource footprints are good proxies of environmental damage. Environ. Sci. Technol. 51, 6360–6366.
Ulucak, R., Lin, D., 2017. Persistence of policy shocks to ecological footprint of the U. S.A. Ecol. Indic. 80, 337–343.
Venetoulis, J., Talberth, J., 2005. Ecological Footprint of Nations 2005 Update. Redefining Progress, Oakland, California, USA.
Wackernagel, M., Onisto, L., Bello, P., Linares, A.C., Falfán, I.S.L., Garćıa, J.M., et al., 1999. National natural capital accounting with the ecological footprint concept. Ecol. Econ. 29, 375–390.
WWF, 2015. Living Planet Report China 2015: Development, Species and Ecological Civilization. WWF Gland, Switzerland, Available from: http://www.wwfchina.org/content/press/publication/2015/Living%20Planet%20Report%20China%202015%20FIN.pdf.
Yang, Y., Hu, D., 2018. Natural capital utilization based on a three-dimensional ecological footprint model: a case study in northern Shaanxi. China. Ecol. Indic. 87, 178–188.
Yang, Y., Ling, S., Zhang, T., et al., 2018. Three-dimensional ecological footprint assessment for ecologically sensitive areas: a case study of the southern qin ling piedmont in Shaanxi, China. J. Clean. Prod. 194, 540–553.
Yang, L., Yang, Y., 2019. Evaluation of eco-efficiency in China from 1978 to 2016: based on a modified ecological footprint model. Sci. Total Environ. 662, 581–590.