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Ecological footprints and development trends in Hefei, China

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Abstract

Purpose – Because natural resource utilization is a predictor of sustainable development, an evaluation of the efficiency of resource utilization is critical for assessing developmental potentiality. The purpose of this paper is to apply three-dimensional (3D) ecological footprint theory to assess the effects of production and consumption on ecological systems in Hefei, China.

Design/methodology/approach – Using data for Hefei for the period 2005-2014, an ecological footprint model (EFM) was developed to calculate the area's ecological footprint (EF), ecological carrying (EC) capacity and obtain two indices, namely, footprint depth and size. The relationship between economic development and natural resource utilization was subsequently evaluated based on the calculated ecological deficit and the EF demand per Renminbi 10,000 of gross domestic product (GDP).

Findings – Over the last decade, Hefei's EF per capita evidenced a 9.87 percent growth rate, increasing from 1.16 hm^2/person in 2005 to 2.70 hm^2/person in 2014. EC capacity per capita increased from 0.21 hm^2/person in 2005 to 0.36 hm^2/person in 2014, evidencing a gradually increasing trend at an average annual growth rate of 6.24 percent. Thus, between 2005 and 2014, the ecological deficit increased annually by three times. The amplification of footprint depth significantly exceeded that of footprint size. Between 2005 and 2014, Hefei's EF per capita Renminbi 10,000 of GDP decreased annually by 4.68 percent. Thus, energy consumption in Hefei exceeded the natural regeneration capacity of energy resources, with excessive development and resource utilization impacting on the regional ecological system.

Practical implications – The application of a 3D EFM sheds light on natural resource utilization within regional development. Moreover, footprint depth and size are significant predictors of the impacts of natural resource utilization. These findings will also benefit other countries or cities.

Originality/value – This is one of the first empirical studies to apply a 3D EFM to evaluate the relationship between natural resource utilization and economic development. Adopting a sustainable development framework, it provides insights into the effects of natural resource utilization in relation to the balance between the natural ecological system and economic development. This has far-reaching implications beyond Hefei and China.

Keywords Sustainable development, 3D ecological footprint, Ecological carrying capacity, Hefei

Paper type Research paper

1. Introduction

The ecological footprint model (EFM) was an ideal intuitive and comprehensive research method to measure the ecological situation, that is, using a specific bio-physical index to measure distinguish whether the development of human being was within the carrying capacity of the ecosystem. The measurement of ecological footprints (EFs), reflecting the EC of land used, is widely applied to assess the degree of sustainable development attained by a society.

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In a socially driven economy, an important component of sustainable development entails conducting an accurate evaluation of the impact of human activities on a regional environment and ecological carrying (EC) capacity. The EF refers to a biologically productive area required to support a given population in a sustainable manner (Wackernagel and Rees, 1996). It provides a measure of the sustainable development of a region based on an estimate of the size of the ecologically productive area required to sustain human consumption of natural resources and assimilation of the associated waste that is generated. This can then be compared with the EC of that area in relation to its population. This paper introduced the three-dimensional (3D) EFM which proposed by Niccolucci *et al.* (2009). The so-called 3D EFM is based on the two-dimensional EF, which distinguishes and traces the natural capital stock through footprint depth and footprint size. The study pointed out that "whether the reduction of capital stock and the extent of its reduction" can be used as a quantitative way to determine the sustainability strength. This is the core issue of sustainable development, especially in response to the ecological economy which recognized by the basic principles of sustainable development (Niccolucci *et al.*, 2009).

In recent years, hi-tech innovations have led to the rapid development of Hefei as a technology driven city. Toward the end of 2014, the Hefei Economic Circle was established in 2009, Hefei was approved by the State Council as a sub-central city within the Changjiang area. Hefei is currently playing an increasingly important role in the economic development of the Anhui and Changjiang economic belts. Up to the end of 2014, the total area of Hefei, including the surface area of Chao Lake (770 km^2), was 11,445.1 km^2. The population of permanent residents of this area was 7.796 million, with an urbanization rate of 70.4 percent. This rapid economic development is causing increasing damage to the surrounding ecology, for example, the outbreak of blue algae. Currently, significant energy consumption, limited land resources, and Hefei's fragile ecological environment are causing problems. During any new urbanization drive, it is critical to ensure that urbanization is carried out strictly on the basis of the carrying capacity of local resources. An assessment of EFs and ECs has, therefore, become an urgent requirement to protect the ecological environment of the entire province, while simultaneously achieving regional sustainable development. The present study is one of the first empirical studies to apply a 3D EFM to evaluate the relationship between natural resource utilization and economic development in a rapidly growing city within a developing country. As a representative of the fast developing cities in the developing countries, Hefei is an important reference for the rapid development new cities in other developing countries, as well as it can be a model city to measure ecological sustainability.

2. Literature review

EF analysis reflects the human impact on the environment, which can transform all kinds of human consumption and activity into land areas. The equivalent or yielding factors in the EF calculation have been used to compare consumption levels in different countries without considering local land productivity, climate, soil properties or techniques conditions, etc. (Haberl *et al.*, 2001). Studies of comparing with other measures of sustainable development show that the EF method is operable and reproducible, and the results can be compared both horizontally and vertically (Luck *et al.*, 2001). The EF method has a wide range of applications since it can be calculated for individuals, families, regions, countries, and even the world's EF. EF can also be used as a decision-making tool because different options or policies are included in method parameters, which can be validated in the EF. For example, a region using coal power generation and water power generation could get different EFs, so as to achieve an objective quantitative comparison of different regions of the implementation of the program. In Spain, 92 dwelling construction projects, which represent the most commonly built dwellings per statistical data from the authorities, are evaluated and their EFs are determined (González-Vallejo *et al.*, 2015). In China, the researcher quantified the carbon, water, and EFs of 17,110 family members of Chinese households, covering 1935 types of foods, by combining survey data with available life-cycle assessment data sets. The data obtained in this study could be used for assessing national food security or the carrying capacity of resources (Song *et al.*, 2015). Therefore, to some extent, this method can help decision makers to develop how to reduce the EF of decision making, and can make people understanding the impact of individual's life style on ecological environment. Thus, the study of EF has become one of the hot fields for many international ecological economists recently.

The concept of an EF was first proposed by the Canadian Ecological Economist, William Rees, in 1996. Subsequently, the theory and methodology associated with the concept was developed and improved by Wackernagel and Rees (1996). The classical theory associated with the EFM entails simple calculations formulated to obtain clear-cut results, thereby effectively simplifying and quantifying the complex problem of human activities and their influence on nature. This model has been widely accepted, globally, as one of the key methods for measuring the degree of sustainable development. Butchart, in collaboration with 45 other scholars from 32 international academic institutions, jointly published an article in *Science* in 2010 that adopted the EF as a key index describing biological diversity. Bian *et al.* (2012) suggested that the most effective way to estimate the overall environmental cost is to calculate the EF based on a study of mineralogy. Lubchenco (1998) noted that a reduction in EFs could result in societies becoming better equipped to face future environmental issues. Wackernagel *et al.* (2004) conducted a study that estimated and compared the total EFs, land type components of EFs, and their evolutionary characteristics in Austria, the Philippines, Korea, and other countries. In the research of Nakajima and Ortega (2016), EC capacity and EF were evaluated using emergy assessment to improve the diagnosis of problems and to make understanding sustainability easier, thereby supporting the formulation of public policies. Kitzes *et al.* (2009) presented a comprehensive review of perceptions and methods around the EF, based on a survey of more than 50 international EF stakeholders and a review of more than 150 original papers on EF methods and applications over the last decade. In recent years, studies conducted on EFs have evidenced a continuous advancement, and this measure has been widely applied in the study of ecology within different fields and at varying levels. With respect to this field, studies on EFs have been expanded from a focus on a single ecological system to a focus on energy (Krivtsov *et al.*, 2004), land (Gerbensleenes *et al.*, 2002), and tourism (Gössling *et al.*, 2002), and their impacts on ecology. Studies on EFs have been conducted on a large scale, encompassing countries (Begum *et al.*, 2009) and regions (Scotti *et al.*, 2009), as well as on smaller scales relating, for example, to companies and families (Crompton *et al.*, 2002). The current study aims to analyze changes in regional EFs and to identify crucial factors affecting these footprints. Based on this analysis, it proposes appropriate measures for promoting sustainable development. Morse and Vogiatzakis (2014) have combined EF theory with the Thompson index to analyze the relationship between various levels of economic development and resource utilization in England. Geng *et al.* (2014) undertook a comparative study of EFs and developmental sustainability in the cities of Shenyang and Kawasaki in China and Japan, respectively, given the similarity of their industrial structures. Li *et al.* (2016) analyzed EFs in arid regions of Northern China from 1999 to 2010 to assess the impacts of urbanization in these areas. Meyfroidt (2017) used carbon footprint models to study carbon emissions. And Xiao *et al.*'s (2017) research found that consumer social risk footprints can help to achieve sustainable development goals.

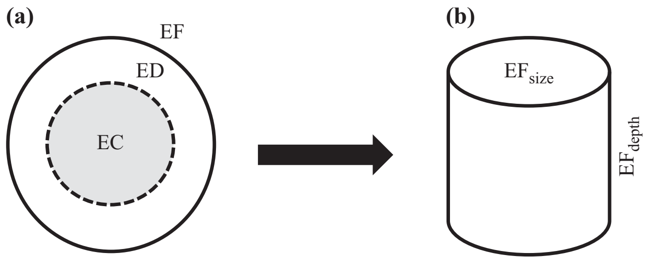
A number of empirical studies that have employed the classical EFM have shown that many parts of the world are experiencing an ecological deficit, with natural resources increasingly becoming key factors constraining social development. However, this classical model has its limitations. One of these is that it has not succeeded in establishing the relationship between flow and stock capital. Moreover, this model does not adequately reflect the temporal dimension of accumulation and the unsustainability of the ecological overdraft. Therefore, Niccolucci *et al.* (2009) proposed the "3D" EF concept that entails the use of new indexes of footprint size and depth to reflect the characteristics of capital flow and consumption. The 3D EFM, which has both spatial and temporal properties, is uniquely capable of revealing equitable differences between resource consumption and service use related to ecological systems during the same time period in areas with different characteristics, or during different time periods in the same area (Niccolucci *et al.*, 2011). More recently, scholars have demonstrated gradually acceptance of evaluations based on the application of the 3D EFM. Niccolucci *et al.* (2011) analyzed global trends in ecological depth and size from 1961 to 2006. Fang and Reinout (2012) further refined the 3D EFM, subsequently applying it in a global evaluation of natural capital utilization (Fang *et al.*, 2013). However, because the short history of the development of 3D EF, the study of the 3D EF is mainly focused on the evaluation of EF and sustainable development. So the research on the EF driving factors from the view of natural capital flow and stock is relatively little (Ma, 2015). At present, the study of urban scale 3D EF accounting is also rarely reported (Bai, 2008; Singh *et al.*, 2009; Rees, 1992).

The 3D EFM used in this study is introduced in the following section, with details provided on data sources. Section 3 analyzes and discusses the use of natural resources in Hefei based on the application of this model. The final section provides an overview of the utilization of natural resources in Hefei, and proposes relevant strategies for future development.

3. Data sources and research methodology

3.1 Research methodology

The calculation of the EF is based on a consideration of two factors (Zhang *et al.*, 2009). The first is that most of the resources, energy, and waste generated by human consumption can be estimated. The second is that all of these resources and waste can be converted into ecologically sustainable land that produces and consumes these resources and waste materials. The 3D EF is based on the classical EF model in which the relationship between the EC and EF is visualized in terms of a two-dimensional plane, as shown in Figure 1(a). However, in the 3D model, the EF, which is visualized in terms of a cylinder, can be obtained by multiplying the area at the bottom, that is, the ecological footprint size (EF_{size}) by the cylinder height, that is, the ecological footprint depth (EF_{depth}), as shown in Figure 1(b). The EF_{depth} of an area denotes the degree of consumption of the natural capital inventory by humans to maintain their existing consumption levels in the area. This degree is actually the accumulated demand on resources beyond the biological carrying capacity, which has a temporal property. The ecological footprint size (EF_{size}) refers to the size that human beings



Notes: (a) ED, ecological deficit; EC, ecological capacity; EF, ecological footprint. (b) EF_{size}, ecological footprint size; EF_{depth}, ecological footprint depth

Figure 1. The transition from a 2D ecological footprint model to a 3D ecological footprint model (Niccolucci *et al.*, 2009)

occupy in the natural capital flow. It has spatial properties and reflects annual land occupation for biological production. The ecological capacity is the upper limit of the natural capital flow provided by the biological cycle, expressed as $0 < \mathrm{EF}_{\mathrm{size}} \leqslant \mathrm{EC}$. The formulae for calculating $\mathrm{EF}_{\mathrm{depth}}$, $\mathrm{EF}_{\mathrm{size}}$, and the 3D EFM are as follows:

$$\mathrm{EF} = N \times ef = N \times \sum_{i=1}^{n} (a_i \times r_j) = N \times \sum_{i=1}^{n} \left(\frac{c_i}{p_i}\right) \times r_j \quad (1)$$

where EF refers to the total ecological footprint, and N is the total population of the region. ef refers to the per capita ecological footprint. a_i represents the bio-productive area which occupied by the ith substance, and r_j is the equilibrium factor. c_i is the per capita consumption of the ith substance, and p_i is the world average production capacity of the ith substance:

$$\mathrm{EF}_{\mathrm{depth}} = 1 + \frac{\mathrm{ED}}{\mathrm{EC}} = 1 + \frac{\sum_{i=1}^{n} \max\{\mathrm{EF}_i - \mathrm{EC}_i, 0\}}{\sum_{i=1}^{n} \mathrm{EC}_i} \quad (2)$$

$$\mathrm{EF}_{\mathrm{size}} = \min\{\mathrm{EF}_i - \mathrm{EC}_i\} \quad (3)$$

$$|\mathrm{EF}_{\mathrm{classic}}| = |\mathrm{EF}_{\mathrm{3D}}| = \mathrm{EF}_{\mathrm{size}} \times \mathrm{EF}_{\mathrm{depth}} \quad (4)$$

where ED refers to the ecological deficit, and EC refers to the ecological capacity. $\mathrm{EF}_{\mathrm{depth}}$ is a magnitude without class, that is, $\mathrm{EF}_{\mathrm{depth}} \geqslant 1$. A greater $\mathrm{EF}_{\mathrm{depth}}$ corresponds to higher consumption of the natural capital stock and to a lower possibility of sustainable development.

The EF per Renminbi (RMB) 10,000 of gross domestic product (GDP) is an indicator of various ecological resources, which is used to calculate the ecological resources consumption of every 10,000 yuan of GDP. It reflects the impact of economic development on land resource utilization, economic growth and technological progress on sustainable development. The greater the index shows the lower the utilization of regional system resource, but on the contrary, it is shows that the region has higher resource utilization. The calculation formula is as follows:

$$\text{The ecological footprint per RMB } 10,000 \text{ of GDP} = \mathrm{EF}/\mathrm{GDP} \times 10,000 \quad (5)$$

3.2 Data sources and selection

The calculation of the index and EF was primarily based on data compiled from various resource and energy consumption projects that were used to define biologically productive land (Zhang *et al.*, 2009; Guo *et al.*, 2003). Six categories of land were identified: arable land, forest land, grassland, water areas, land used for obtaining fossil fuels, and land used for construction. Consumed biological resources included crop products, stock farming products, forestry products, aquatic products, as well as at least 15 other items. Crop products include wheat, rice, wheat, maize, cotton, peanut, oilseeds, hemp, and vegetables. Forest products are mainly a variety of garden fruits and tea (fruit and tea are classified as forest products according to the growth pattern of fruit trees and tea trees). Animal products include pork, beef, lamb, dairy and poultry eggs and fisheries containing aquatic products. The annual output of various biological accounts is checked in the Anhui Statistical Yearbook. The primary energy sources were raw and refined coal, coke, gasoline, diesel, and electrical heating consumed during construction activities. Using methods that are applied internationally, the heat consumed in Hefei is converted into fossil fuels during construction, with calorific value per area of production land per fossil fuel unit (Wackernagel and Rees, 1998).

Research data were compiled from the Anhui Statistical Yearbook (2010-2015), the Hefei Statistical Yearbook (2010-2015), and the Statistical Bulletin of National Economy and Social Development (2010-2015) published on the Hefei Statistical Bureau website. The latest available statistical yearbook was for the year 2015. Consequently, research data were extracted up to 2014. The average production output from projects required for the calculation of EFs was derived from the statistical database created by the Food and Agriculture Organization of the United Nations.

3.3 Equivalence and yield factors

The concept of an equivalence factor was introduced to convert the production capacity of different types of land into a unified and comparable biological production value. This factor denotes the ratio between biologically productive land within a region to the area all productive land average productivity. The yield factor denotes the ratio of the average productivity of a certain type of land in a particular region to the same type of productive land globally. Reference was made to past research results and the standards for calculating EFs, published by the Food and Agriculture Organization in 1993, were applied. Table I shows the equivalence and yield factors used in the calculation of the EF (Wackernagel *et al.*, 2005).

4. Results and analysis

4.1 Analysis of Hefei's EF

Hefei's 3D EF was calculated using formulae (1)-(3) for the period 2005-2014. Figure 2 shows that over the last decade, Hefei's EF per capita increased from 1.16 square hectometer/person (hm^2/person) in 2005 to 2.70 hm^2/person in 2014, indicating a 9.87 percent growth rate. While the EF per capita showed fluctuating growth prior to 2009, it subsequently showed continuous growth during the latter period from 2009 to 2014. In 2011, the EF increased by 52.60 percent compared with its value in 2010. This substantial increase was attributed to changes in Hefei's administrative divisions. In 2011, Chaohu, a prefectural city, was divided into Lujiang County and a county-level Chaohu city. Chaohu includes a water area that is overseen by the Hefei administration (Tang *et al.*, 2009). Within Hefei, Chaohu and Lujiang County are supply bases of agricultural and light industrial products. Consequently, there has been a significant rise in Hefei's EF commencing from 2011. Figure 2 indicates that the primary sources of Hefei's EF were land used for obtaining fossil fuels and arable land accounting for 33.80 and 50.57 percent, respectively, of the EF per capita that year. During the last decade, the EF of fossil energy increased at a rate of 12.84 percent, which was the fastest rate observed for all EFs. This implies that Hefei's economic development is still at a stage of continuous expansion. There has been a tremendous acceleration of industrialization, with significant increases in the consumption

Land type	Equivalence factor	Yield factor
Arable land	2.82	1.66
Forest land	1.14	0.91
Grassland	0.54	0.19
Water area	0.22	1.00
Land for construction	2.82	1.66
Land for fossil fuel	1.14	0.00

Note: The equivalence and yield factors were published by the Food and Agriculture Organization in 1993

Table I. Equivalence and yield factors

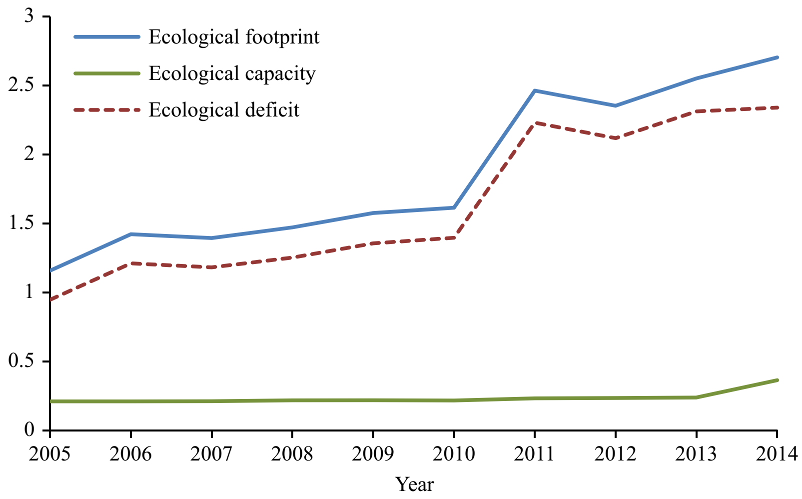


Figure 2.
The trend for Hefei's ecological footprint per capita (2005-2014) (hm^2/p.)

of coal, gasoline, heat, and other sources of energy. The most significant change in the EF per capita was observed for coal, which has increased by 27.73 percent over the last decade. Evidently, the consumption of coal-based energy is still prevalent in Hefei. Efforts to improve sustainable development and utilize clean energy are, therefore, urgently required in this area. Arable land accounted for a large proportion of the area's total EF. However, its EF showed an annual decrease of 1.46 percent from 2011 to 2013. This decrease was linked to accelerated urbanization and an annual decrease in the area of arable land.

Figure 2 shows that the EC per capita increased from 0.21 hm^2/person in 2005 to 0.36 hm^2/person in 2014, indicating a gradually increasing trend with an average annual growth rate of 6.24 percent. As indicated in Figure 2, the EC per capita showed a relatively smaller change than the EF per capita. Therefore, between 2005 and 2014, the ecological deficit increased annually by three times. Moreover, these trends relating to the ecological deficit are consistent with the EF. The main sources of deficit per capita in Hefei are land used to obtain fossil fuels, arable land, the water area, and grassland, all of which are contributing factors in the creation of a significant ecological deficit per capita, with a resultant increase in ecological pressure. However, surplus land for construction purposes is available. In 2011, Hefei expanded and emerged as one of China's largest cities as a result of administrative restructuring. However, Hefei's urbanization has not yet led to a significant ecological deficit because of the vast amount of land available for construction purposes. Even so, the problem of ecological deficit in Hefei is still serious, and the filling of ecological deficits mainly comes from the import or exploitation of capital stock. Hefei's external dependence is higher, which input a lot of resources and energy from the surrounding cities of Hefei. But we should see that trade brings import resources, and Hefei ecological environment basically bear all the pollutant emissions. And it is not all resources can be available through imports, such as land resources. So the ecological deficit is an important indicator of environmental governance.

In the period from 1998 to 2008, the annual growth rate of urban ecological capacities of Nanjing (Feng and Xiao Ying, 2009), Tianjin (Guo and Huang, 2008), and Shenzhen (Wu *et al.*, 2008) was −13.75, −8.48, and −31.48 percent, which was very different from that of Hefei. Conversely, Hefei's ecological capacity has gradually increased every year, evidencing what is clearly an increasing EF. There may be two reasons for this phenomenon. First, production efficiency has improved as a result of the adoption of technology rather than because of an expanding production area. Second, because the Hefei administrative area is large, certain land resources can be utilized with an annual increase in arable, forest, and construction land. The pressure on land resources in Hefei is relatively less than the pressure on these resources in Nanjing, Tianjin, and Shenzhen.

4.2 Ecological size and depth

EF_{depth} reflects the consumption of natural resource stocks in one area. From 2005 to 2014, the trends of EF_{size} and EF_{depth} are basically the same which is increasing. Hefei's EF_{depth} per capita showed an annual increase of 7.68 percent, and the gap between the highest year 2014 and the lowest year 2005 was 5.19. EF_{size} per capita simultaneously increased by 1.37 percent, and the lowest year in 2005 with the highest year 2013 had a difference of 0.15, which was relatively lower compared with the increase of the EF_{depth}. Because the natural capital flow was insufficient for supporting increasing consumption in this area, capital stocks should be consumed appropriately to sustain development. According to the different trends, ten years can be divided into three stages: in the first stage from 2005 to 2009, the EF_{depth} and the EF_{size} were showing a slow growth trend, indicating that Hefei was in the high-speed economic development and preparation stage. In the second stage, the EF_{size} and the EF_{depth} were more obvious than that of the previous stage, and the EF_{depth} in 2012 showed a significant decrease. This showed that with the further development of the economy, the EF_{depth} was faster than the previous stage, and the volatility was larger than the previous period. In the third stage, the EF_{depth} and the EF_{size} varied greatly from 2013 to 2014, and the EF_{depth} decreased by 16.62 percent compared with the previous year, while the EF_{size} increased by 23.47 percent in the same year.

As revealed by the trends for EF_{depth} and EF_{size} displayed in Figure 3, the amplification of the former was significantly larger than that of the latter. This reveals that the pressure and intensity of use to which Hefei's ecological environment is being subjected are increasing. Because of the lack of natural capital flow, or its constriction, there is overreliance on the consumption of the natural capital stock to maintain a balance between the supply and demand, which has become characteristic of regional social economic development. In general, high consumption of capital stock is closely related to low occupation of flow capital, along with a high population density, low resource endowment, and limited natural capital flow. A scientifically based structure of resource utilization in

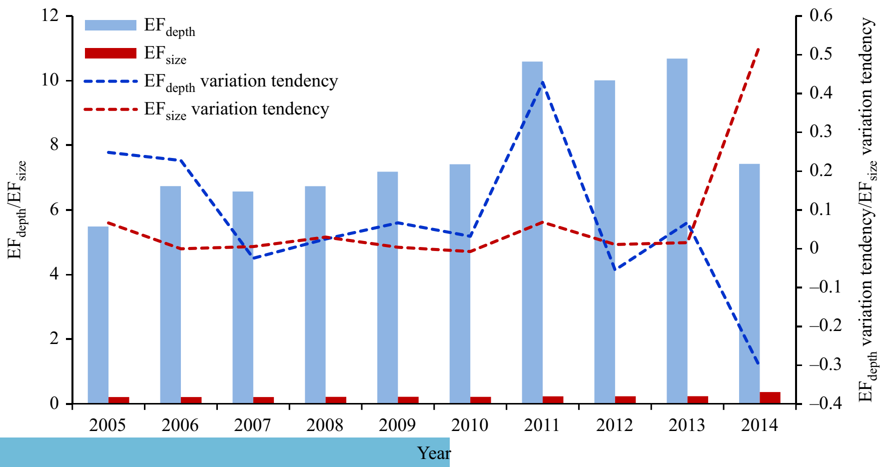


Figure 3.
Ecological footprint depth and size per capita and the rate of change in these two indexes

one area should be aimed at preserving as much of the natural capital stock as possible, and efficiently using the natural capital flow. The mobility of the regional capital flow may be limited because of geopolitical and economic factors.

4.3 EF per RMB10,000 of GDP

Production and human life are closely related to resource utilization. The demands placed by regional or national economic activities on the EF per capita RMB10,000 of GDP to some extent reflect utilization efficiency and economic benefits of regional or national biological resources. The larger the EF per capita RMB10,000 of GDP, the lower both the output per unit of biologically productive land and resource utilization efficiency will be in the region. Conversely, resource utilization efficiency in the region will be higher with a smaller EF per capita RMB10,000 of GDP. Figure 4 shows that with the exception of 2011, the EF per capita RMB10,000 of GDP in Hefei decreased annually by 4.68 percent from 2005 to 2014. The EF per capita RMB10,000 showed a decline in 2014 at a value of 0.400 hm^2/person compared with the value of 0.51 hm^2/person in 2011. This indicates that an improvement in the resource utilization level in Hefei occurred in conjunction with economic development. Evidently, in recent years, Hefei has widely availed of scientific technology in relation to production to improve resource utilization efficiency and reduce the resultant wastage. Moreover, trend analysis revealed that the direction of per capita GDP growth was opposite to that of EF per capita RMB10,000 of GDP. The EF per capita RMB10,000 of GDP for most of the years during the period 2005-2014 showed a tendency to decrease, indicating that economic development in Hefei has resulted in an improved living standard for the city's residents. Therefore, there has been a gradual corresponding increase in resource consumption per capita. With the use of modern technological innovations, the output per unit of biologically productive land has increased, that is, resource utilization efficiency has increased. To some extent, this has reduced pressure on the environment caused by increasing resource consumption. Thus, optimal use of technology to fuel economic development in a particular area is an effective way of improving sustainable development in the area.

5. Conclusion

This study utilized the 3D EF concept and calculations based on a statistical analysis to examine Hefei's EF and relevant indexes for the period 2005-2014. A model based on capital

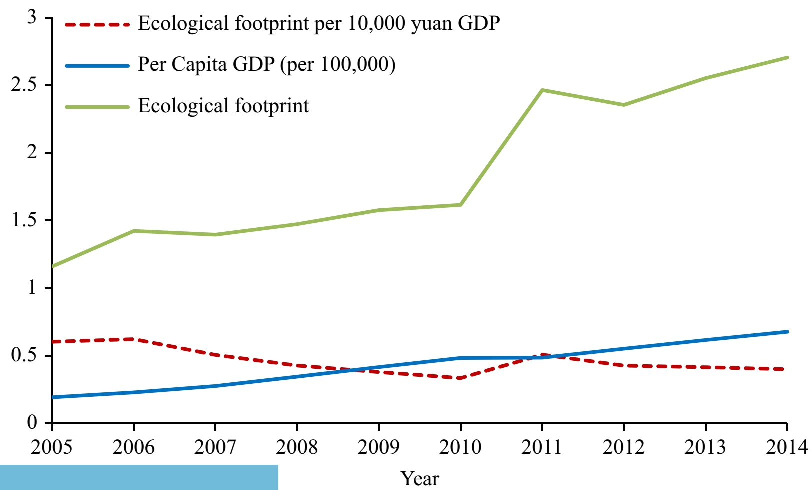


Figure 4.
A trend analysis of Hefei's ecological footprint per capita RMB10,000 of GDP for the period 2009-2014

flows and stocks was used to analyze the sustainability of regional development. This model combined the advantages of the classical EFM, while enhancing temporal and spatial comparability. This is one of the first empirical studies to use a 3D model to evaluate the relationship between natural resource utilization and economic development in a rapidly growing city within a developing country.

The empirical analysis revealed an increase in Hefei's EF between 2005 and 2014. Moreover, the EF in 2011 showed an increase of 52.60 percent compared with the EF in 2010. Of all the components contributing to EFs, land used to obtain fossil fuel was the most significant. This finding indicates that Hefei's economic development is highly dependent on energy resources such as coal. Hefei's EC also showed an annual increase between 2005 and 2014. However, its growth rate was much lower than that of EFs. Hence, the ecological deficit increased by nearly three times during the last decade. This means that the consumption of energy resources by Hefei's population exceeded their natural regeneration capacity. Moreover, the regional ecological system has been subjected to excessive development and resource utilization. Natural resource stocks in Hefei have been excessively consumed, both in spatial and temporal terms, because of a lack of congruence with the natural resource flow. Moreover, the disparity between the flow of natural resources and their stocks is increasing every year. At the same time, Hefei's EF per RMB10,000 of GDP deceased annually by 4.68 percent between 2005 and 2014. This indicates that the increasing use of technology has enhanced economic production in Hefei, in addition to improving resource utilization and efficiency. Although there is a serious contradiction between economic development and natural resources in Hefei, the city's per capita EC continues to show an average annual increase rate of 6.24 percent. Thus, compared with other cities, between ecological environment and social development has a bigger room to ease. There may be two reasons for this phenomenon. First, production efficiency has improved as a result of the adoption of technology rather than because of an expanding production area. Second, because the administrative area of Hefei is large. Studies of comparing with the economically developed cities show that Hefei own more land resources. So the pressure on land resources in Hefei is relatively less than the pressure on these resources in Nanjing, Tianjin, and Shenzhen.

In order to promote the ecological sustainability of Hefei, the following measures can be taken: first, Hefei is China's emerging science and education city, with many of China's well-known universities and research institutes. Hefei should rely on the latest research results of universities and research institutes. Second, we should encourage the development of the tertiary industry in Hefei, which is mostly clean and environmentally friendly service industry. The development of the tertiary industry reduced the destruction of the ecological environment and increased the number of jobs. Third, we should vigorously promote new energy to replace traditional energy sources, according clean production to improve energy efficiency. As a result, the pressure of economic activities on natural ecosystems will be reduced. Fourth, we should strengthen the natural capital compensation flows between Hefei and other regions. The structure of natural capital flows and natural capital stock should be greatly improved; thereby we can restrain the reduction of natural capital stock due to economic development. So that the sustainability of the natural capital stock will remain unchanged. In addition, we should strive to strengthen the management of natural resources, population management and urban infrastructure of the ecological production of social system, to improve the urbanization process.

This paper makes a preliminary study on the sustainability of natural capital utilization in Hefei through the 3D EFM. Due to the availability of data and the limitations of the research methods, the selection of evaluation indicators is not perfect. In the future, we need to further study the driving mechanism of the 3D EF.

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