Article

Henan Ecological Security Evaluation Using Improved 3D Ecological Footprint Model Based on Emergy and Net Primary Productivity

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Abstract: The ecological footprint (EF) model is an effective tool for determining whether natural assets are over-utilized. The traditional EF (TEF) model and its improved model which include the emergy ecological footprint (EEF) and net primary productivity ecological footprint (NPPEF) have been widely used, but some emergy data are hard to obtain and NPP data is not stable. Therefore, in this paper, a novel three-dimensional (3D) EF model with emergy and net primary productivity (3DEF-ENPP) is proposed. The Henan province of China was chosen as the research area and commonly used statistical yearbook data and NPP data were used which are easy to obtain. We expanded a 2D EF model to a 3D EF model and took advantage of emergy analysis and net primary productivity because they have stable energy parameters, can reflect the difference in bioproductivity of different land types, and are suitable for spatial and temporal analysis. Based on our model, we obtained a rectified emergy-based ecological footprint (REEF), an ecological capacity based on net primary productivity (RNPPEC), a rectified ecological deficit (RED), an ecological footprint intensity (EFI), an ecological coordination coefficient, and a 3D-EF, which can comprehensively reflect Henan’s ecological security status. The results show that: (1) The REEF and RNPPEC obtained by our proposed model are more stable than those of the former method. (2) Henan’s RED has been negative and has a downward trend, which indicates the burden of human activities on the natural environment are becoming increasingly serious. (3) The EF is increasing with time, indicating that the consumption of natural resources in Henan is gradually increasing. High EF regions are mainly distributed in the northwestern area. Southeastern regions have relatively low EFs. (4) Capital flows cannot meet the needs of current social development in Henan province and it is in a state of unsustainable development. (5) The ecological stress index is at a safe state but is still at an ecological security warning level and Henan has good ecological coordination.

Keywords: ecological footprint; ecological capacity; ecological deficit; emergy; NPP; 3DEF-ENPP

1. Introduction

With rapid economic development and rapid population growth, the impact of human activities on the earth’s ecosystem is growing, bringing about more and more serious problems such as the contradiction between natural resources, the environment, and the economy. It leads to resource depletion and environmental degradation. Hence, sustainable development has become the consensus of the whole of society. In recent years, the Chinese government has vigorously promoted the construction of ecological civilization. It published a regional green development index in December
In order to achieve sustainable development, it is necessary to evaluate the current state of the regional ecosystem. Evaluation methods are continuously improving and the measurement of environmental sustainability has gradually evolved from qualitative analysis to quantitative analysis. The ecological footprint model was initially proposed by Wackernagel and Rees, and involves quantitatively evaluating the degree of sustainable utilization of resources through accounting and comparing the gap between the demand of the human economic system on natural ecosystem services and the carrying capacity of the natural ecosystem. Because of its visual and clear calculation results and regional comparability, it has been widely used in the measurement of sustainable development.

The ecological footprint (EF) model is important, and it is therefore necessary to improve the EF model to make it better reflect the ecological status of the target area. Research at the province level and spatial distribution of cities in one province is scarce. There is no recent research (starting from 2007) about ecological security in the Henan province of China and the cities of Henan. Therefore, the scientific interests of this study focused on the following: (1) proposing a three-dimensional (3D) EF model with an emergy and net primary productivity (3DEF-ENPP) model, which improves upon the traditional EF model, and (2) comprehensively evaluating the ecological security status of Henan Province (a typical province in central China) and its cities from 2007 to 2016 using the proposed 3DEF-ENPP model. This study is meaningful in that it provides an academic reference for ecological sustainability analysis, and it also provides a scientific basis for sustainable development strategies in that can be employed in the construction of ecological civilization in other provinces.

The structure of this paper is as follows. Firstly, we introduce the background of our research and the scientific interests of our study. Secondly, a literature review introduces the traditional ecological footprint model, modified/improved EF models and their classification, and the emergy analysis model and NPP-based model and their application. We summarize their advantages and disadvantages and introduce our model. Thirdly, the research area and data are introduced. The data are open, more reliable, and more accurate than emergy data. Fourthly, we introduce the method in detail. Fifthly, we present our results and discussion. Lastly, we summarize our research and introduce future study.

2. Literature Review

1. Traditional ecological footprint model and its application. In the 1990s, the EF model was proposed by Rees and Wachernagel. The model, namely the traditional ecological footprint (TEF) model, is an effective means of undertaking qualitative analysis of environmental sustainability [1,2]. The EF model transforms the issue of sustainable development evaluation into quantitative analysis of land area. The calculation results are straightforward and regionally comparable, and therefore it quickly received widespread concern among research institutions, international organizations, the government, and the public. It has become a popular field in today’s sustainable development research and an important model for measuring environmental sustainability [3–5]. A lot of scholars have studied the application of EFs. For example, Yao et al. have analyzed the spatial and temporal patterns of the EF and ecological capacity (EC) of Wuhan city, finding that the ecological footprint increased in fluctuations from 1.48 gha per capita to 2.10 gha per capita, with the carbon footprint contributing most. Within the whole time period of the declining biocapacity of the region, a gradually aggravated ecological deficit in the city was observed, which increased from 1.12 gha per capita in 1995 to 1.79 gha per capita in 2008 [6,7] Wang calculated and analyzed the ecological footprint of Xi’an from 1999 to 2014 by adding environmental pollution to the EF model, arriving at the conclusions: (1) Water pollution control and water area development are core issues in the Xi’an eco-city development. Air pollution control and forest land development also play important roles in the eco-city development. (2) Eco-city practices contribute to decreases in per capita EF and per capita ecological deficit because of the reduction in the EFs of water area, forest land, and arable land. (3) The effects of
Sustainability 2019, 11, 1353 3 of 23

eco-city practices on the improvement of per capita ecological capacity, and the ECs of arable land, water areas, pasture land, and forest land are not significant [8]. Chen et al. evaluated the EC of the tourism industry in Zhoushan City from 2010 to 2014 by EF analysis. The results showed that the tourism EF and local EF slowly increased between 2010 and 2014. EF accounted for a remarkable proportion over this five-year period and reached 20–30% of the regional EF. Although the EF of Zhoushan was slightly over its carrying capacity, the per capital EF of residents remained below average national and global levels. Proper planning and development of tourism at the regional level are suggested as a sound strategy for sustainable development of the Zhoushan municipality [9,10].

2. Modified EF models and their classification: At present, many scholars have further expanded the EF model and its application; it can now be divided into EF models based on life cycle assessment (LCA) [11,12], EF models based on input-output analysis [7,13], EF models based on NPP (NPPEF) [14], and EF models based on emergy (written with “m”) (EEF) [15]. An EF model based on LCA is suitable for the EF assessment of the whole life cycle of a single product like steel or cement but is not applicable to regional research. EF models based on input-output analysis study the ecology from an economic perspective and require a large amount of statistical economic data. EEF and NPPEF are applicable to the study of ecological environment issues in regions such as cities, provinces, and countries [16]. Considering the available research data and that the research object is a region rather than a single product, EEF and NPPEF are the two main EF models discussed in this paper.

3. The emergy analysis (EA) model and its application: The Emergy analysis method [17] was created by the famous American ecologists Odum and Arding in the late 1980s, and is used for assessing the functions of natural assets and ecosystems. Based on EA, EEF is used to convert incomparable energies of different eco-economic systems to energy values of the same standard for measurement and analysis [18]. Compared with the parameters of TEF models such as the equalization and production factors, which are very controversial, EEF uses the energy conversion rate, energy density, and other parameters, which are more stable and have more practical value. The energy conversion rate can also reflect a certain economic development status and technical level. Zhao et al. (2005) first modified the EF calculations by combining them with emergy synthesis calculations. This new methodology was applied in an analysis of the Gansu province of China and it was concluded that both methods have corresponding biological productivity units [18]. Due to the advantages of this hybrid model, EEF studies on regional development have been carried out. For example, Chen has investigated the resource consumption of Chinese society by using EF and emergent ecological footprint models and suggested using emergent ecological footprint as a modified indicator of EF [19]. Peng et al. improved upon the EEF model to evaluate the sustainability of the city of Qingdao from 2004 to 2014. Their study integrated labor services, fixed set investment, and the output value of high-tech industries into supply capacity and provided a dynamical prediction of regional development [20]. Yang et al. analyzed the dynamic changes of ecological security of China’s provinces based on EEF indicators to predict national or regional ecological security. The study provided valuable insights into how to guide the sustainable development of urban systems. However, human activities within urban systems are producing various pollutants. The impact of these pollutants has been ignored by these EEF-based studies [21].

4. NPP-based models and their application NPP has begun to be applied in the improvement of the EF model in recent years. Venetoulis linked EF with NPP and proposed the NPP-based EF calculation model [14], namely NPPEF, which is a hotspot and frontier in this research field. NPPEF makes up for some of the shortcomings of the TEF model, such as the mutual exclusion hypothesis of land function (which is unreasonable), the equalization and yield factor distortion, and the neglect of ecological functions. The TEF model often uses global equivalence and global production factors, which cannot reflect local realities to some extent, but the equalization and
yield factor based on local NPP is more related to local environmental conditions. NPPEF reveals the relationship between human activities and ecosystem services more clearly. It provides a deeper understanding of biological production and consumption chains from an ecosystem dynamics perspective and reflects the exchange of biomass between regions. Technically, real-time NPP information can be quickly obtained using remote sensing and geographic information systems [22]. Liu Moucheng has analyzed the ecological footprint of different areas at the regional scale and calculated the production coefficient at a national level and provincial level based on the net primary productivity (NPP) from MODIS data with 1 km resolution in 2001. They found that at a national level, the production coefficient of cropland was 1.74, which meant that the cropland productivity in China was bigger than the global average. At the provincial level, the production coefficient differed between provinces because the NPP of different land use types in different regions was varied [23]. Liu Xiaoman and Fu Jingying have improved the ecological footprint model based on net primary productivity (the NPPEF model). Based on the TEF model, the status of ecological footprints and the EC of 319 national nature reserves in 2010 was explored, and the changes in ecological surpluses and ecological deficits from 2000 to 2010 were analyzed. The EF per capita and the EC per capita calculated by the two models were mostly consistently at the same level, which indicated that the EF per capita and the EC per capita of the two models followed the same rule [24]. Lu and Yao used the ecological footprint model based on net primary productivity and MODIS data to measure the ecological footprint in the Xuzhou central area from 2005 to 2014. The results showed that from 2005 to 2014, the EF per capita increased from 1.06 to 1.17 hm²/capita, the EC per capita decreased from 0.10 to 0.09 hm² per capita, the ED per capita increased from −0.96 to −1.09 hm² per person, and the ecological pressure index increased from 6.87 to 11.97. Grassland contributed most to the EF and ED and cultivated land contributed most to the EC. The spatial distribution of the ecological footprint changed significantly, especially in the expansion of the areas of lower value. The ecological capacity and deficit changed little. The ecological situation in the Xuzhou central area was imbalanced [25]. EEF and NPPEF have been widely used and have some advantages over the TEF model, but each also has flaws: (a) In the EEF model, EC is equal to the maximum value of various natural energies such as wind energy, solar energy, and chemical potential energy. These energy data are difficult to measure, the accuracy is low, and there is no uniform specification. (b) When using NPP to calculate EF, the result will have large fluctuations because NPP data is unstable [16]. Ways to avoid the disadvantages of EEF and NPPEF and to take the advantage of them have never been studied. EEF combined with the NPP model can take advantage of the stability of EEF parameters and can also use NPP to reflect the bio-productivity differences of different land types. Based on this, we have proposed a three-dimensional EF calculation model based on energy and NPP (3DEF-ENPP), which combines energy analysis with the NPP model and expand the 2D EF model to a 3D EF model. We took advantage of energy analysis in that it has stable energy parameters and advantage of NPP in that it can be used to reflect the difference in bio-productivity of different land types and is suitable for spatial and temporal analysis. The disadvantages of the energy model, namely, that the parameters and data are difficult to measure and have low accuracy, were avoided, and we proposed using a convolutional filter to reduce the large fluctuations of NPP. The Henan province of China was chosen as the research area and commonly used statistical yearbook data and NPP data were used, which are easy to obtain. Based on our model, we obtained a rectified energy-based ecological footprint (REEF), an ecological capacity based on net primary productivity (RNPPEC), a rectified ecological deficit (RED), an ecological footprint intensity (EFI), an ecological coordination coefficient, and a 3D-EF, which can comprehensively reflect Henan’s ecological security status. The improvements of the proposed model and former model are displayed in Figure 1.
EF, which can comprehensively reflect Henan’s ecological security status. The improvements of the proposed model and former model are displayed in Figure 1. Figure 1. The improvement of the proposed 3DEF-ENPP model. Legend: TEF, Traditional ecological footprint; EF, ecological footprint; EC, ecological capacity; ED ecological deficit; EEF, ecological footprint based on emergy; EEC, ecological capacity based on emergy; NPPEF, ecological footprint based on net primary productivity; NPPEC, ecological capacity based on net primary productivity; REEF, rectified EEF; RNPPEC, rectified NPPEC; RED, rectified ecological deficit; 3DEF-ENPP, three-dimensional ecological footprint model with emergy and net primary productivity.

3. Research Area and Data

3.1. Research Area

This paper selected Henan Province as the research area, a province which is located in the central and eastern parts of China. Henan is a typical central plain area located in the middle and lower reaches of the Yellow River between 110° 21′ and 116° 39′ east longitude and 31° 23′ to 36° 22′ north latitude (see Figure 2). It is an important agricultural and economic province. As per the “Thirteenth Five-Year Plan Draft”, Henan will focus on building an ecological big data project and an ecological supervision system. The key to these big projects is to quantitatively model the regional ecology, and the EF model plays an important role in quantitatively modelling the regional ecology.
3.2. Data Sources

1. NPP: NPP was obtained from the standard data product of NASA’s MOD17A3 (http://ladsweb.nascom.nasa.gov). The time period used was from 2007 to 2016, the spatial resolution was 1 km, and the unit is KgC/(year·m²) (kg of carbon per year m²). Currently, MOD17A3 is widely used in the detection of regional vegetation growth, biomass estimation, and global change. Firstly, the grayscale outlier was eliminated and the pixel value of the MOD17A3 data was converted to the NPP value according to the scale factor; then, the MODIS data was mosaic and reprojected using the MODIS reprojection tool software provided by NASA, using the Albers Equal-product projection; then, it was tailored using the Henan Province administrative map of national basic geographic information data.

2. EF account data: EF account data included (a) natural resource consumption accounting data and (b) productive land area data. The data were obtained from the Henan Statistical Yearbook (2007–2016).
   a. Natural resource consumption accounting includes biological resource consumption and energy consumption. Biological resource consumption is mainly based on the daily consumption of people in Henan, including food, vegetables, cooking oil, pig, beef and mutton, poultry, fresh eggs, fish and shrimp, fresh milk, and wine. Energy consumption includes coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, natural gas, heat, and electricity.
   b. Productive land data include areas of fisheries, orchards, vegetables, crops, and urban area.

3. Land use (LU) data: Henan LU data for 2005, 2010, and 2015 were obtained from the geographical Information Monitoring Cloud Platform (http://www.dsac.cn/). The data were based on the interpretation of a Landsat remote sensing image and was verified by field investigation. The Landsat remote sensing image was from the USGS website; in the process of interpreting the image, field investigation verification was conducted to strictly control the data. The data quality is authentic and reliable and has an accuracy of around 95%.

4. Demographic data: The population data used in this study are resident population statistics, mainly from the Statistical Yearbook of Henan Province (2007–2016).
4. Research Methods

In this study, the status of the ecological security of Henan and 18 cities from 2007 to 2016 were comprehensively calculated and analyzed according to the following process (Figure 3).

4.1. Workflow of Proposed 3DEF-ENPP Model

The proposed 3DEF-ENPP model combines NPP, emergy and 3DEF to comprehensively analyze the ecological security of the study area. It is shown in Figure 3 that the main process of 3DEF-ENPP model is as follows:

(a) We proposed that NPP be smoothed by a one-dimensional and 2D convolution filter so the large fluctuations in NPP could be reduced.

\[
NPP_{i,j} = \sum_{i}^{m} \sum_{j}^{n} w_{i,j} NPP_{i,j}
\]

\[
NPP_{t} = \sum_{i}^{m} m_{i} NPP_{t-1}
\]

NPP was spatially smoothed by the first equation. \( i \) and \( j \) are the locations of NPP pixels in the NPP image data and \( w \) is the weight matrix. \( m \) and \( n \) are the width and length of the NPP image, respectively. After NPP is spatially smoothed, it is temporally smoothed by Equation (2). \( t \) is the year (from 2007 to 2016). \( m \) is the weight matrix and \( k \) is length of the window of a one-dimensional convolution filter (here we chose 3).

(b) The LU and NPP data were overlaid and we obtained NPP values for different land types. Because the available LU data was for the years 2005, 2010, and 2015, the LU year closest to NPP was overlaid with NPP. Hence, the LU data of 2005 and NPP of 2007 were overlaid, the LU data of 2005 and NPP from 2008 to 2012 were overlaid, and the LU data of 2005 and NPP values from 2013 to 2016 were overlaid. The NPP values were then used to calculate equalization and production factors of different land types.

(c) An ecological footprint account and demographic data were used. The EF was calculated by an EEF model, namely EEF. EC was calculated based on the equalization factor and production factor using NPP, which is NPPEC.

(d) The EF and EC were calculated by the TEF model and were used as a reference to rectify EEF and NPPEC based on a linear regression method, from which we obtained a REEF (rectified EEF) and RNPPEC (rectified NPPEC), respectively. The results of both the EEF and NPPEC were linearly rectified while the trend could be kept.

\[
y = \text{LinearRegression} (x) = kx + b
\]

The formula is as follows: \( x \) is the independent variable and \( y \) is the dependent variable, \( b \) is the fitting coefficient constant (intercept) and \( k \) is the \( x \) coefficient (slope). RNPPEC and REEF are able to maintain the trend of EC and EF after they are linearly rectified.

(e) Based on the RNPPEC and REEF, the EFI, Ds, and 3DEF were calculated and the results and analysis are given.
4.2. TEF Model

In the TEF model, EF and EC are calculated. The ecological impact of human activities and urban construction are transformed into an EF and the resources of the region are transformed into an EC. EF and EC can be used to quantify and assess the continued development of the region [3,15].

1. To calculate EF, the biological resource footprint and energy footprint need to be calculated.
   
   (a) To calculate the biological resource footprint, the biological resources and energy resources consumed by humans are converted into corresponding bio-productive areas (bio-productive land is divided into six types: cultivated land, grassland, forest land, water areas, construction land, and fossil energy land). Because different ecologically productive land areas have different ecological effects and different ecological productivities, and given that EF is a comprehensive index, the calculated bio-productive areas also need to be equalized by equivalence factors. The equivalence factors used in general are: 2.82 for cultivated land and construction land, 1.10 for forest land, 0.54 for grassland, 0.2 for water, and 1.14 for fossil energy use [5].

   (b) To calculate energy consumption it is necessary to convert it into a fossil energy land area. This is based on the fact that CO₂ emitted at the same fossil energy consumption rate needs to absorb the corresponding CO₂ land area. The global average fossil energy land conversion coefficients of coal, oil, natural gas, and hydropower given by Wachernagel et al. are 55, 71, 93, and 1000 GJ/hm²a, respectively [3], and the energy consumption can be converted into the corresponding fossil energy land area by conversion factors. Based on the above description, the general formula for calculating the EF is:

   \[
   EF = N \times ef = N \times \sum_{i=1}^{n} r_j \times (aa_i) = N \times \sum_{i=1}^{n} r_j \times (c_i/p_i)
   \]  

   \(EF\) is the ecological footprint (hm²), \(N\) is the total population, \(ef\) is the EF per capita (hm²/capita), \(i\) is the type of consumption item, \(j\) is the bio-productive land type, \(r_j\) is
the equivalence factor, \( a_i \) is the bio-production area of the \( i \)-th consumption item per capita (hm\(^2\)/capita), \( c_i \) is the consumption (ton) of the \( i \)-th item per capita per year (ton/capita-year\(^{-1}\)), and \( p_i \) is the average productivity (ton) of the \( i \)-th item per hm\(^2\) per year (ton·hm\(^{-2}\)·year\(^{-1}\)).

2. When calculating \( EC \), the selected land use types are: construction land, water, cultivated land, orchards, and vegetable land. The status of ecological resources in different regions is not always consistent, so it is not possible to directly compare and calculate. The usual approach is to adjust the different types of areas and use the production factor, i.e., the yield factor, to correct them. The yield factors used in this example are: 1.91 for construction land, 0.85 for water, 1.91 for cultivated land, 2.54 for orchards, and 1.24 for vegetable land [3]. The general formula for calculating the EC is

\[
EC = N \ast ec = N \ast \sum_{j=1}^{5} a_j \ast r_j \ast y_j
\]  

where \( EC \) is the total ecological capacity, \( N \) is the total population, \( ec \) is the \( EC \) per capita, \( j \) is the \( j \)-th bio-productive land type, \( a_j \) is the bio-productive land area per capita (hm\(^2\)/cap), \( r_j \) is the equivalence factor and \( y_j \) is the yield factor.

4.3. Emergy-Based EF Model

Emergy is a tool used to assess the function of natural assets and ecosystems. The emergy analysis of an EF involves measuring, analyzing and transferring energy values of different types and incomparable energies into the same standard based on emergy [15,18]. The formula for calculating the emergy ecological capacity is

\[
EEC = N \ast eec = N \ast e / p
\]  

where \( EEC \) is the emergy ecological capacity (hm\(^2\)); \( N \) is population; \( eec \) is \( EEC \) per capita (hm\(^2\)/a); \( e \) is the solar energy value per capita (sej/capita) of renewable resources; and \( p \) is the density of regional average emergy (sej·hm\(^{-2}\)), which refers to the ratio of the total emergy of the renewable resources in the region to the regional land area. When calculating EC, solar radiant energy, wind energy, rainwater chemical energy, rainwater potential energy, and the Earth’s rotation are mainly considered. The energy values of these five renewable resources and the solar energy conversion rate of each renewable resource can be found in the literature. Since wind energy, rain energy potential, and rainwater chemical energy are the transformation forms of sunlight in energy flow, in order to avoid double counting, according to energy value theory, only the maximum energy values are selected. Therefore, the total emergy value of the renewable resources is equal to the maximum of the first four energy values plus the energy value of the Earth’s rotational energy. The formula for calculating the EEF is

\[
EEF = N \cdot eef = N \cdot \sum_{i=1}^{n} (c_i / p)
\]  

where \( EEF \) is the emergy ecological footprint (hm\(^2\)), \( N \) is the population, \( eef \) is the \( EEF \) per capita (hm\(^2\)/capita), \( c_i \) is the emergy value of the \( i \)-th resource per capita (sej/capita), and \( p \) is the average emergy density of the region (sej·hm\(^{-2}\)).

4.4. Equalization Factor and Production Factor Calculation Based on NPP

1. Equalization factor calculation: The average NPP of four types of bio-productive land (cultivated land, forest land, livestock land, and fishery land) was calculated from the NPP of each vegetation cover type and its area:

\[
P_{NP} = \frac{\sum P_i A_j}{\sum A_j}
\]  

P_{NP} is the average NPP, P_j is the NPP of a certain vegetation type (gC·m^{-2}·a^{-1}), and A_j is the area of a certain vegetation type (m^2) [14]. In this case, the NPPs of different land types are obtained by the overlay of remote sensing and land use data. We needed to calculate the equalization factor of six bio-productive land types (cultivated land, forest land, livestock land, fishery land, construction land, and fossil energy land) in total. The energy consumption footprint is characterized by the forest land area required for CO_2 generated by energy consumption; the equivalence factor of fossil energy land is equal to forest land. Construction land takes up agricultural land, so the equivalence factor of urban construction land is equal to that of farmland. The equivalence factor \( r_j \) of farmland, woodland, livestock land, and fishery land was obtained by dividing the NPP of a certain type of bio-productive land by the average NPP of the four types of land [22]:

\[
    r_j = \frac{P_i}{P_{NP}} \tag{9}
\]

\( r_j \) is the equalization factor of land type \( i \), \( P_i \) is the NPP of a certain type of bio-productive land (gC·m^{-2}·year^{-1}), in C, and \( P_{NP} \) is the average NPP of these four types of land (g·m^{-2}·year^{-1}), calculated in C, with reference to Equation (4).

2. Yield factor: Since the energy consumption footprint is characterized by the area of forest land needed to absorb CO_2 generated by energy consumption, the production factor of fossil energy land is taken as zero; construction takes up more agricultural land, so the yield factor of urban construction land is still equal to the yield factor of agricultural land. The production factors of agricultural land, forest land, livestock land, and fishery land are calculated as

\[
    y_j = \frac{\text{NPP}_j}{\text{NANPP}_j} \tag{10}
\]

where \( \text{NANPP}_j \) is the national average NPP of \( j \)-th bio-productive land type and \( \text{NPP}_j \) is the local average NPP of \( j \)-th land-use type. In this case, the yield factors of the four types of land in China (agricultural land, forest land, livestock land, and fishery land) are 741.47, 598.96, 188.89, and 148.23 (gCm^{-2}a^{-1}) [14].

4.5. Evaluation Method of Ecological Security

1. The ecological deficit (ED) is calculated as [26]

\[
    ED = EC - EF = N \cdot ed = N \cdot (ec - ef) \tag{11}
\]

where \( ED \) is the ecological deficit (hm^2) and \( ed \) is the ecological deficit per capita (hm^2/capita). When \( ED \) is negative, \( EC \) is less than demand and the research area is in a state of ecological deficit; when \( ED \) is positive, \( EC \) is greater than demand and the research area is in state of ecological surplus; when \( ED \) is zero, \( EC \) is equal to demand and the research area is in an ecologically balanced state.

2. Ecological footprint intensity (EFI): This is also known as the ecological stress index. EFI represents the extent to which a regional environment is under pressure and is calculated as

\[
    EFI = EF / EC \tag{12}
\]

where \( EFI \) is the ecological stress index, \( EF \) is the ecological footprint, and \( EC \) is the ecological capacity. When \( EF > 0, EC > 0 \), and \( 0 < EFI < 1 \), i.e., \( EF < EC \), the supply of ecological resources is greater than the demand. The pressure on the area is small, and the area is in an ecologically safe state. When \( EFI > 1 \), i.e., \( EF > EC \), the pressure on the area is greater than its supporting capacity, that is, the ecological resources are less than the demand. The ecological security of the area is threatened, and the greater the difference between \( EFI \) and 1 is, the greater degree of
ecological insecurity. According to the range of ecological pressure index values, ecological safety levels and ecological safety warning levels (Table 1) can be divided visually to reflect regional ecological security status.

Table 1. Division of ecological security levels and alarm. Legend: EFI, ecological footprint intensity.

<table>
<thead>
<tr>
<th>Ecological Security Grade</th>
<th>Level</th>
<th>Range of EFI</th>
<th>Ecological Security Alarm Level</th>
<th>Level</th>
<th>Range of EFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Safe</td>
<td>0–1.0</td>
<td>0</td>
<td>No alarm</td>
<td>0–1.0</td>
</tr>
<tr>
<td>2</td>
<td>Less safe</td>
<td>1.0–10.0</td>
<td>1</td>
<td>Low alarm</td>
<td>1.0–6.0</td>
</tr>
<tr>
<td>3</td>
<td>Slightly dangerous</td>
<td>10.0–18.0</td>
<td>2</td>
<td>Moderate alarm</td>
<td>6.0–10.0</td>
</tr>
<tr>
<td>4</td>
<td>Moderate dangerous</td>
<td>18.0–24.0</td>
<td>3</td>
<td>High alarm</td>
<td>10.0–15.0</td>
</tr>
<tr>
<td>5</td>
<td>High dangerous</td>
<td>24.0–30.0</td>
<td>4</td>
<td>Severe alarm</td>
<td>15.0–20.0</td>
</tr>
<tr>
<td>6</td>
<td>Extremely dangerous</td>
<td>&gt;30.0</td>
<td>5</td>
<td>Extreme alarm</td>
<td>&gt;20.0</td>
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3. Ecological coordination coefficient \( D_s \): The ecological coordination coefficient indicates the coordination between the economic and social development of a region and the local ecological environment. The calculation formula is

\[
D_s = \frac{ef + ec}{\sqrt{ef^2 + ec^2}} = \frac{ef + 1}{\sqrt{\left(\frac{ef}{ec}\right)^2 + 1}} = \left(\frac{EFI + 1}{\sqrt{EFI^2 + 1}}\right)
\]

where \( D_s \) is the regional ecological coordination coefficient, \( ef \) is the local EF per capita, and \( ec \) is the EC per capita. \( ef \) and \( ec \) are both > 0 and 1 < \( D_s \) ≤ 1.414. The closer \( D_s \) is to 1, the worse the ecological coordination of the region; the closer \( D_s \) is to 1.414, the better the regional ecological coordination is; and when \( D_s = 1.414 \), the regional ecological demand and supply are balanced, indicating that the regional ecological coordination is in optimal state.

4.6. 3D-EF Model

Based on the TEF model, which is two-dimensional, Niccolucci introduced ecological footprint depth (\( EF_{\text{depth}} \)) and ecological footprint size (\( EF_{\text{size}} \)) to explain the human occupation of natural resource flows and natural resource stocks, expanding the traditional 2D plane TEF model to a temporal and spatial 3D model. In this way, the vertical expansion of TEF research was achieved. The evolution process of the TEF model from being two-dimensional to being three-dimensional is shown in Figure 4. The 3D model regards EF as a cylinder, and it includes the multiplication of footprint breadth and footprint depth in a similar fashion to the concept of planetary boundaries [27–29].

When the \( EF \) is smaller than the ecological productive land area that the region can provide, \( EF_{\text{size}} \) is used to characterize the occupation of natural resources by human activities. The \( EF \) is \( EF_{\text{size}} \); when the \( EF \) is larger than the ecological productive land area that the region can provide, \( EF_{\text{depth}} \) is introduced to characterize the occupation of natural resources by human activities. \( EF_{\text{depth}} \) is equal to the ratio of the \( EF \) to the area of ecological productive land that the region can provide. This ratio can be expressed as the number of years needed to reproduce the resource consumption of one year. \( EF_{\text{depth}} \) can be considered as an indicator that reflects the regional ecological pressure on a time scale.

In the three-dimensional model, the following relationship exists:

If \( EF - EC < 0 \), then:

\[ EF_{\text{size}} = EF \quad (14) \]

If \( EF - EC > 0 \), then:

\[ EF_{\text{size}} = EC \quad (15) \]
EF\(_{\text{size}}\) is the ecological footprint size, EF\(_{\text{depth}}\) is the ecological footprint depth, and EF\(_{\text{depth}}\) \(> 1\). BC and ED represent ecological capacity and ecological deficit in the 2D model, respectively; EF\(_{\text{depth}}\) \(\geq 1\); and when EF \(\leq EC\), EF\(_{\text{depth}}\) = 1.

![Figure 4. EF model evolving from two dimensions to three dimensions.](image)

The EF\(_{3D}\) formula is as follows:

\[
EF_{3D} = EF_{\text{size}} \cdot EF_{\text{depth}}
\]

(17)

EF\(_{3D}\) is the 3D ecological footprint, EF\(_{\text{size}}\) is the footprint size, and EF\(_{\text{depth}}\) is the footprint depth.

5. Results and Discussion

5.1. EF Results Based on the TEF Model

Firstly, the TEF model was used to calculate the EF spatial distribution from 2007 to 2016 and is shown in Figure 5. It can be seen that high EF regions are mainly distributed in the northwestern area, which is because that area is the most populated and the consumption of biology is high [30]. However, the southern regions have relatively low EF values. The southern regions are farmland areas and have a lesser population, so the consumption of biology is relatively low [31]. The spatial distribution pattern is stable from 2007 to 2016 and the EF value varies from 1 to 3.8.

![Figure 5. Cont.](image)
Figure 5. Cont.
5.2. EF Results Based on the EEF Model

EF calculation results of cities in Henan using the EEF model are displayed in Figure 6 (Figure 6a is enlarged to display the city locations more clearly).

Figure 5. Spatial distribution of EF per capita in Henan province for 2007–2016 based on the TEF model.

Figure 6. Cont.
Figure 6. Spatial distribution of EEF per capita in Henan province from 2007 to 2016.

It can be seen from Figures 5 and 6 that the spatial distributions of the EFs in Henan cities for the EEF and TEF models are the same, proving that the EEF results are correct. The EFs of Zheng Zhou, Luo Yang, Ji Yuan, Jiao Zuo, and San Menxia are high (shown in Figure 6a). Because Zheng Zhou is the capital city of Henan Province and Luo Yang is the second largest city in Henan, their population concentration and GDP per capita is high, which causes high consumption in each area. Ji Yuan, Jiao Zuo, and San Menxia are resource-intensive cities in which the consumption of natural resources is large [32]. Ji Yuan is an area which produces raw coal. At the same time, the consumption of raw coal of Ji Yuan is huge [31]. Raw coal occupies the most important component in Henan’s
EEF (as is concluded in Table 2), so the ecological footprint of Ji Yuan City is high. San Menxia has many large hydropower stations in the Yellow River and has high resource consumption. The EEFs of Zhu Madian and Zhou Kou are lowest because they are agricultural production bases and have relatively low populations [33]. The EEF values of each city in Henan vary from 3 to 16 and TEF values vary from 1 to 3.8. EEF and TEF have differences because they belong to different system and model. Fengxian [32] and Jia Junsong [34] have studied the EF of Henan as a whole unit. Our study not only studies Henan but also the inner cities, the distribution of EF, and the reason for there being high or low EFs. Also, the time period Fengxian used was from 1990 to 2007, whereas we used the latest data and studied EFs of Henan from 2007 to 2016. Jia Junsong studied the EF of Henan from 1949 to 2006 and used an autoregressive integrated moving average (ARIMA) model to predict the EF of Henan from 2007 to 2015. Our EF research can be used as verification of Jia Junsong’s study, which is a future research topic.

5.3. Statistical Analysis

1. EF calculation: The statistical EF results of the TEF per capita, the EEF per capita and the NPPEF per capita of Henan are shown in Figure 7. In general, EFs of three figures show an upward trend over the years (from 2007 to 2016), which is in alignment with the conclusion about Henan of former researcher Fengxian [32] that Henan’s EFs are steadily increasing and have a upward trend. This proves the results of the EEF and NPPEF models can correctly reflect the EF of Henan. Results of the TEF show the largest fluctuations while results of EEF show the smallest functions in a scatter plot graph. This proves that EF calculated by EEF is more stable than that of other two models, because EEF uses energy parameters which are more stable than the equalization factor and production factor calculated by NPP and the traditional model. Pearson’s r is the Pearson correlation coefficient, which is a measure of the linear correlation between two variables X and Y. Pearson’s r of the EEF is higher than that of EF and NPPEF, which means that EEF has best correlation with the years. Table 2 shows the emergy of biological resource consumption and fossil consumption, both of which are increasing, and the fossil energy consumption ratio, which gives a ratio of fossil energy consumption to total consumption of around 84%, indicating the consumption of natural resources is increasing and fossil energy accounts for a large proportion. Coal accounts for an average of 56% of fossil fuel consumption.

2. EC calculation: The results of the NPPEC and TEF models are shown in Figure 8. The overall trends of EC and NPPEC are similar; the shape is the same but the values are different (EC varies from 0.93 to 0.99 and NPPEC varies from 0.262 to 0.280) because are different models. Pearson’s r for EC is higher than that of the NPPEC, which means that EC has better correlation with the years. Generally, it can be seen from Figure 8 that Henan’s EC and NPPEC show a stable trend over the years, but the value gap exists because they are from different calculation systems (from Figure 9).
The results of the EEF and NPPEC models correctly reflect the changes in the trend and the spatial distribution of EF and EC in Henan province, but it is difficult to compare EEF with NPPEC and calculate ED and EFI directly because their bases are different models. Pearson’s r for EC is higher than that of the NPPEC, which means that EC has better correlation with the years. Generally, it can be seen from Figure 8 that Henan’s EC and NPPEC show a stable trend over the years, but the value gap exists because they are from different calculation systems (from Figure 9).

In the linear fitting process of EC, NPPEC is the independent variable while the EC is the dependent variable. R² is 0.634 > 0.5, the fitting constant coefficient is 1.73, and the x coefficient is 0.049. The results of the EEF and NPPEC models are shown in Figure 8. The overall trends of EC and NPPEC vary from 0.262 to 0.280 because they are from different models. Pearson’s r for EC is higher than that of the NPPEC, which means that EC has better correlation with the years. Generally, it can be seen from Figure 8 that Henan’s EC and NPPEC show a stable trend over the years, but the value gap exists because they are from different calculation systems (from Figure 9).

### Table 2. Emergy of biological resource consumption and fossil energy consumption of Henan.

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<tbody>
<tr>
<td>Biological resource consumption</td>
<td>6.85 × 10²²</td>
<td>8.34 × 10²²</td>
<td>8.75 × 10²²</td>
<td>8.85 × 10²²</td>
<td>8.92 × 10²²</td>
<td>9.11 × 10²²</td>
<td>8.99 × 10²²</td>
<td>8.8 × 10²²</td>
<td>1.07 × 10²³</td>
<td>1.11 × 10²³</td>
</tr>
<tr>
<td>Fossil energy consumption</td>
<td>3.85 × 10²³</td>
<td>4.02 × 10²³</td>
<td>4.4 × 10²³</td>
<td>4.37 × 10²³</td>
<td>4.8 × 10²³</td>
<td>4.81 × 10²³</td>
<td>4.97 × 10²³</td>
<td>4.99 × 10²³</td>
<td>5.04 × 10²³</td>
<td>5.03 × 10²³</td>
</tr>
<tr>
<td>Fossil energy consumption ratio</td>
<td>0.85</td>
<td>0.83</td>
<td>0.83</td>
<td>0.83</td>
<td>0.84</td>
<td>0.84</td>
<td>0.85</td>
<td>0.85</td>
<td>0.82</td>
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### Figure 7.
- (a) TEF per capita of Henan
- (b) EEF per capita of Henan
- (c) NPPEF per capita

### Figure 8.
- (a) EC per capita of Henan in past years
- (b) NPPEC per capita of Henan in past years

3. REEF, RNPPEC, and RED calculation

The results of the EEF and NPPEC models correctly reflect the changes in the trend and the spatial distribution of EF and EC in Henan province, but it is difficult to compare EEF with NPPEC and calculate ED and EFI directly because their bases...
and calculation systems are different. To solve this, we proposed that TEF calculation results be used as reference to rectify EEF and NPP-EC based on a linear regression method. Further, the results of both EF and NPP-EC may be linearly rectified while keeping the trend, so the correct ecological security evaluation index can be obtained. In the linear fitting process of EC, NPPEC is the independent variable while the EC is the dependent variable. R² is 0.916, suggesting that the fitting results of model are in good performance. Further, the empirical statistical equation shows that the fitting coefficient constant is −0.037 and the x coefficient is 3.694, which is illustrated as follows (RNPPEC is a rectified NPPEC and REEF is a rectified EEF).

\[
\text{RNPPEC} = 3.694 \times \text{NPPEC} - 0.037
\]

In the linear fitting process of EF, EEF is the independent variable and EF is the dependent variable. R² is 0.634 > 0.5, the fitting constant coefficient is 1.73, and the x coefficient is 0.049.

\[
\text{REEF} = 0.0049 \times \text{EEF} + 1.73
\]

The RNPPEC and the REEF are shown in the Figure 10a, b. The EEC and the RNPPEC have the same upward trend but have a slight difference. Both the EF and the REEF show an upward trend, but the EF fluctuates greatly while the EEF fluctuates less. This proves that linear regression did not change the trend and that the EEF is more stable. Both RED and ED have a downward trend and the values are negative, indicating that Henan’s ecological environment is under pressure and gradually worsens with time.

![Figure 9](image)

**Figure 9.** Results of NPPEC per capita and traditional EC per capita.

![Figure 10](image)

**Figure 10.** (a) Comparison between rectified NPPEC (RNPPEC) and EC; (b) comparison between rectified EEF (REEF) and EF.
The results show that RNPPEC, REEF, and ED are correct and more stable than the former result. Obtaining stable and accurate EF results is very necessary and important because tasks such as EF spatial and temporal simulations [5,35], which are used for more refined regional management and political planning, need stable and accurate EFs. EF spatial and temporal simulations are calculated by a traditional machine learning model (Lingyan’s work used a back propagation neural network) or a deep learning model (Gong’s research used a deep recurrent neural network), which needs very stable and accurate data or the accuracy will be low and not reliable. Our results testify that our proposed model has more stable results.

4. 3DEF, EFI, and Ds calculation: The 3DEF of Henan Province shows a significant upward trend, as shown in Figure 11b and Table 3. 3DEF is steadily increasing, which means the ecological pressure on Henan is increasing. \( EF_{\text{size}} \) and \( EF_{\text{depth}} \) are shown in Figure 11c. \( EF_{\text{size}} \) represents the capital flow occupancy. \( EF_{\text{size}} \) changes from 0.9 to 1 \( \text{hm}^2 \). This reflects the fact that capital flows cannot meet the needs of the current social development of Henan province. \( EF_{\text{depth}} \) represents the level of capital stock consumption. \( EF_{\text{depth}} \) changes from 2.1 to 2.2 \( \text{hm}^2 \), which exceeds the original value of 1, meaning that Henan is in a state of unsustainable development. This shows that the capital flow occupancy can no longer meet regional development resource demand, and large amounts of capital stocks are therefore consumed.

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<tbody>
<tr>
<td>3DEF</td>
<td>2.04</td>
<td>2.06</td>
<td>2.08</td>
<td>2.09</td>
<td>2.12</td>
<td>2.12</td>
<td>2.13</td>
<td>2.13</td>
<td>2.14</td>
<td>2.14</td>
</tr>
<tr>
<td>EFI</td>
<td>2.12</td>
<td>2.18</td>
<td>2.23</td>
<td>2.2</td>
<td>2.19</td>
<td>2.19</td>
<td>2.19</td>
<td>2.17</td>
<td>2.16</td>
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<tr>
<td>Ds</td>
<td>1.331</td>
<td>1.326</td>
<td>1.322</td>
<td>1.324</td>
<td>1.325</td>
<td>1.325</td>
<td>1.327</td>
<td>1.327</td>
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In Table 3, EFI and Ds remain stable, indicating that ecological stress and the correlation between the development of a region and the local ecological environment are relatively stable. Henan’s EFI is in the range of 2.18, greater than 1 and less than 10, which means the ecological stress index is in a safe state but is still at an ecological security warning level. Henan’s Ds is around 1.32, indicating that the study area has good ecological coordination. Former research [30,31,36] has only studied a 2D-EF of Henan, with the results only reflecting whether the EF is in deficit or not; we have comprehensively reflected natural resource flows, natural resource stocks, 3DEF, EFI, and Ds, which will be very useful in future ecological management and planning.

![Figure 11. Cont.](image-url)
Figure 11. (a) Rectified ecological deficit (RED) and ED per capita for Henan over the years, (b) 3DEF of Henan over the years, and (c) ecological footprint depth (EF\text{depth}) and ecological footprint size (EF\text{size}) per capita over the years.

6. Conclusions and Prospects

Research at the province level and for spatial distribution of cities in one province is scarce. There has been no recent research (starting from 2007) about ecological security in the Henan province of China and the cities of Henan. We have effectively and comprehensively evaluated the ecological status of Henan with the application of a proposed 3DEF-ENPP model. We used data which is open to the public and published every year by the government. This data is easier to obtain and more reliable than that used for the former model. The results of our model are more stable than for the TEF, and can be used for EF spatial simulations and temporal predictions, because these need accurate and stable EF data. Use of the three-dimensional model can explain whether it is overloaded in the horizontal direction and the degree of overload in the vertical direction and can analyze the occupancy of human natural resource consumption on resource flows and resource stocks.

The results show:

1. The REEF and RNPPED obtained via our proposed model are more stable than those of the former method and have high correlation with years.
2. Henan’s RED has been negative and has a downward trend, indicating the burden of human activities on the natural environment are becoming increasingly serious.
3. EF is increasing with time, indicating that the consumption of natural resources in Henan is gradually increasing. High EF regions are mainly distributed in the northwestern area and this spatial distribution is stable. The southeastern regions have relatively low EFs. The EC and NPPEC show a stable trend.
4. Capital flows cannot meet the needs of current social development of Henan Province and the province is in a state of unsustainable development.

5. The ecological stress index is in a safe state but still is at an ecological security warning level, and Henan has good ecological coordination.

The results of the EEF also show that fossil energy consumption is increasing and accounts for a great proportion of the EF. Coal resources account for the largest proportion of fossil energy consumption. This coal-based energy structure is determined by the level of the economy and the composition of local resources and is the most important factor contributing to haze in northern China. Governments and enterprises should develop more efficient and environment-friendly production methods and use clean and renewable energy. The government should pay attention to environmental protection policies, guide the development of the economy, encourage the development of enterprises with low pollution and high economic efficiency, and establish people’s awareness regarding saving energy.

This study chose the city as the research unit. The grid is the commonly used research unit in geographic analysis because it has more refined spatial distribution. Knowing how to apply the EF model from the city or region to the grid is the next research goal. The current data used in this research are mostly statistical data. Knowing how to apply more satellite remote sensing data, which is low-cost, fast, objective, and accurate for EF calculation, is also the next challenge we face.

Author Contributions: Writing—original draft, G.C.; supervision, Q.L.; investigation, B.T. and S.F.; writing—review and editing, H.K. and B.T.; data curation, F.P.; methodology, G.C.

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Conflicts of Interest: The authors declare no conflict of interest.

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