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Evaluating the Sustainability of Nature Reserves Using an Ecological Footprint Method: A Case Study in China

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Abstract: Nature reserves are established to protect ecosystems and rare flora and fauna. However, with the rapid development of the social economy, many nature reserves are facing enormous pressures from human activities. The assessment of the sustainability of nature reserves is a fundamental task for the planning and management of such areas. In this study, the sustainability of China's 319 national nature reserves (NRRs) was evaluated based on an ecological footprint (EF) method. The results indicated that the per capita ecological footprints of all national nature reserves increased 85.86% from 2000 to 2010. Meanwhile, the per capita biocapacity (BC) of all national nature reserves increased slightly, with a rate of increase of 1.79%. The 'traffic light' method was adopted to identify the sustainability status of those national nature reserves. It was found that currently (2010) 45% of NRRs were in the condition of ecological deficit. In terms of dynamic changes in EF and BC, only 16% of NRRs were sustainable. The 124 national nature reserves that were in the red light state were mainly distributed in Anhui Province, Chongqing City, Hunan, Guizhou, Fujian, Shandong Province, and Inner Mongolia. The percentage of nature reserves at the red light state in these areas were 83.3%, 66.7%, 64.7%, 62.5%, 58.3%, 57.1%, and 56.5%, respectively. The reserves in the red light state should be included in the priority concern level and should be strictly controlled in terms of population growth and the intensity of exploitation. The results of this study will provide more effective data for reference and for decision making support in nature reserve protection.

Keywords: national nature reserves; sustainability; ecological footprint method; 'traffic light' method

1. Introduction

Nature reserves are protected areas of importance for natural ecosystems, rare and endangered species of wild fauna and flora, and important objects such as natural monuments. The ecosystems in nature reserves are usually valuable and relatively fragile, so better protection is essentially always needed [1]. In China, more than 2590 nature reserves of different types, including 319 national nature reserves (NRRs), have been established. The total amount of protected area is more than 149 million hectares, including 143 million hectares of land and 6.37 million hectares of marine environment [2]. With the rapid development of the social economy, resource development and construction projects such as mines, hydropower stations, and tourism activities have imposed huge pressures on the local environment and ecosystems [3–5]. Pursuing sustainable development requires a better understanding of the choices before us [6], and monitoring and evaluating the sustainability of those special areas is of great importance for the effective management of these areas.

The ecological footprint (EF) concept offers a methodologically simple but comprehensive way to examine whether society lives within its ecological capacity. The EF represents the critical natural capital requirements of a defined economy or population in terms of its corresponding biologically productive areas [7]. EF accounting is one of the most comprehensive ecological economic indicators for measuring the fundamental conditions for sustainability [7–9]. It is a resource and emissions accounting tool that measures direct and indirect human demand of the planet's regenerative capacity (biocapacity, BC) and compares that with the BC available on the planet [10]. The ecological footprint and carrying capacity have been considered to be two of the main criteria of sustainability [11–13] due to the simplicity of the comparison of EF and BC, which suggests a clear distinction between sustainability and unsustainability [14,15]. The EF-based method has been widely used at global [16,17], national [17–19], and local scales [20,21].

The aim of this paper was to present insights into the dynamic changes in the sustainability of NRRs in China with an EF-based method. First, the EF and BC of 319 NRRs in China from the years 2000 and 2010 were calculated. Second, the dynamic changes in EF, BC, and the difference between them were analyzed. Finally, the sustainability of all NRRs was evaluated, and its driving forces were discussed. The results will provide more effective data for reference and for decision making support in nature reserve management.

2. Methods

2.1. Data Acquisition

In this research, the world's average yield data was obtained from the Food and Agriculture Organization of the United Nations [22]. The energy data used in this research was derived from China's energy statistics yearbook in 2000 and 2010 [23,24], and the population data came from the fifth census (2000) and the sixth census in China (2010) [25,26]. The land-use data in the nature reserves came from the "Remote Sensing Investigation and Assessment of the National Ecological Environment in the Decade Changes (2000–2010)" project, which was a project of the Ministry of Environmental Protection of the People's Republic of China [27]. The main objective of this project was to extract the national land-use data mainly based on the optical satellite remote sensing data with 30 m spatial resolution. And 31,675 ground sample points were used for calibration. The evaluation results showed that the average accuracy of the first class of the land-use data was 96%, and the average accuracy of the second class of the land-use data was 91% [27].

2.2. Methodology

Four steps were performed to evaluate the sustainability of nature reserves:

(1) Calculation of the per capita ecological footprint:

The EF of a certain region (nature reserve) is the sum of each product and can be calculated using the formula (1) [28]:

$$EF_{nr} = \sum_{j=1}^{n} \frac{C_j}{EP_j} \times r_j \qquad (1)$$

where EF_{nr} is the total EF of a nature reserve, C_j is the amount of consumption of each primary product j, EPj is the annual average yield of production for land type j, and r_j is the equivalence factor for the land-use of type j. The per capita ecological footprint can be calculated using formula (2) as follows:

$$ef_{nr} = EF_{nr}/N \qquad (2)$$

where ef_{nr} is the per capita ecological footprint and N is the population of a nature reserve [29].

(2) Calculation of the per capita biocapacity:

The biocapacity and the per capita biocapacity are calculated using Equations (3) and (4), respectively [28]:

$$EC_{nr} = \sum_{i=1}^{n} A_j \times r_j \times y_j \quad (3)$$

$$ec_{nr} = EC_{nr}/N, \quad (4)$$

where ec_{nr} is the biocapacity of a nature reserve, A_j is the bio-productive area of land type j, r_j is the equivalence factor for the land-use of type j, y_j is the region-specific yield factor for the land producing product j, ec_{nr} stands for the per capita biocapacity, and N is the population of the nature reserve. Detailed explanations of the ecological footprint and biocapacity calculations can be found in [28,29].

(3) Comparison of the per capita EF and the per capita BC:

The per capita EF of a nature reserve can be compared with its per capita BC. If the EF is bigger than the available BC, which is often interpreted as 'ecological deficit', it defines a situation where human consumption exceeds the ecological limits [14,30]. Alternatively, if the per capita EF is smaller than the per capita BC, this is considered to be an 'ecological surplus'.

(4) Classifying the condition of sustainability of NRRs:

The condition of sustainability of NRRs can be classified into three classes and six sub-classes using the 'traffic light' method (Table 1).

Table 1. Classification of the sustainability of national nature reserves (NRRs).

Sustainability	Per Capita Ecological Surplus/Deficit
1. Green light	1.1. Ecological deficit changed into ecological surplus
	1.2. Increase of ecological surplus
2. Yellow light	2.1. Decrease of ecological surplus
	2.2. Decrease of ecological deficit
3. Red light	3.1. Ecological surplus changed into ecological deficit
	3.2. Increase of ecological deficit

3. Result and Analysis

3.1. Variation in The Per Capita EF from 2000 to 2010

In general, the per capita EF for all NRRs increased from 1.91 ha to 3.56 ha from 2000 to 2010 (Figure 1). The EF demands of 87.8% of the NRRs increased during this period and decreased only for 12.2% of the NRRs. Three categories of biologically productive areas mainly contributed to the ecological footprints, which were farmland, grazing land, and built-up land, accounting for 46.89%, 25.08%, and 18.51% of the total EF, respectively. The results also indicated that during the period from 2000–2010, the per capita EF of built-up land increased approximately 1.6 times, from 0.65 ha to 1.67 ha, which greatly impacted the ecosystems within the NRRs. The per capita EF of farmland and grazing land increased 67.92% and 43.48%, respectively.

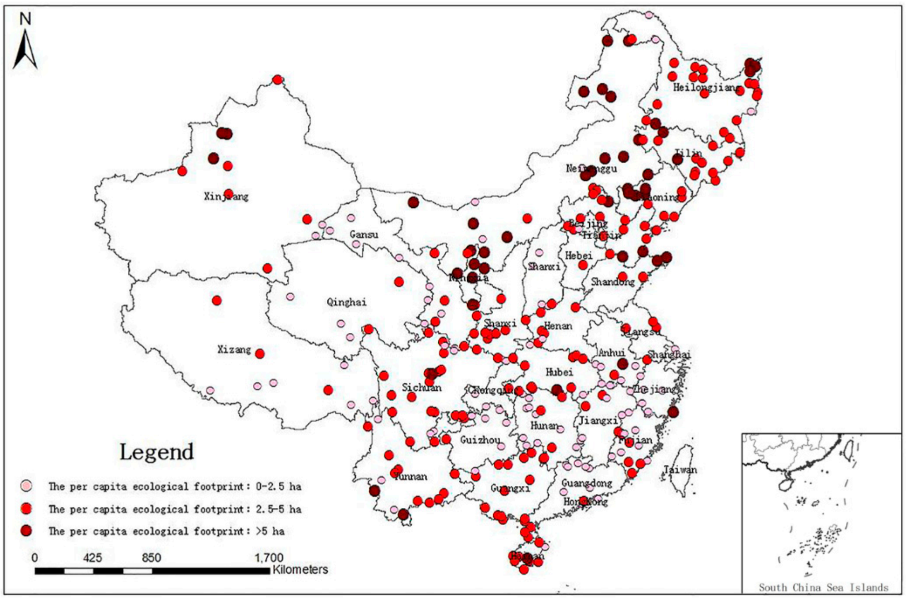

Figure 1. The spatial distribution of the per capita ecological footprints of the 319 national nature reserves of China in 2010.

Meanwhile, the per capita BC of NRRs in China increased slightly and reached 3758.9 ha in 2010. Grazing land, forest land, and water contributed 83.7% of the total BC. Although the BC is much larger than the EF in general, the difference between them varied dramatically among nature reserves. Figure 2 shows the spatial distribution of the per capita ecological surplus (or deficit) of the 319 NRRs of China in 2010. It shows that in the year 2010, 142 NRRs (accounting for 44.5% of the total) were in the condition of ecological deficit (EF > BC, marked as red points in Figure 2). Those NRRs are mainly distributed in Guizhou, Anhui, Liaoning, Inner Mongolia Province, and Chongqing City. Another 177 NRRs (55.5% of the total) were in a condition of ecological surplus (EF < BC, marked as green points in Figure 2), and these mainly occur in Tibet, Xinjiang, Ningxia, Heilongjiang, and Hainan Provinces.

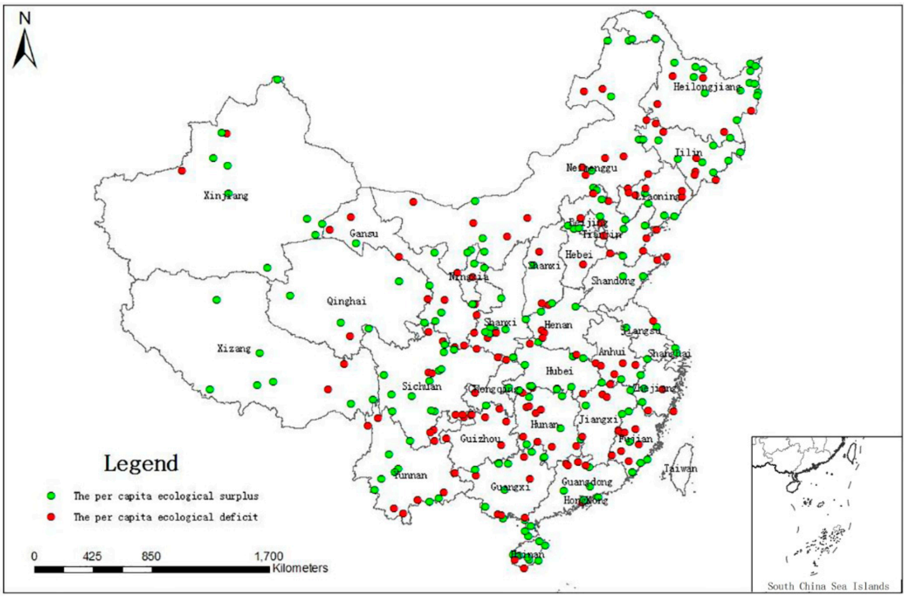

Figure 2. The spatial distribution of the per capita ecological surplus (or deficit) of the 319 NRRs of China in 2010.

3.2. Variation in the Per Capita EF from 2000 to 2010–Evaluation of the Sustainability of Nature Reserves

The EF and BC are two criteria for evaluating regional sustainability [31]. To present an in depth analysis of the ecological sustainability of national nature reserves in China, the 'traffic light' method [32] was adopted in this research. The EF and BC together with their dynamic changes were used and all of the NRRs were classified into three groups: red light, yellow light, and red light. The green light represents a condition of ecological surplus and an increasing trend in the ecological surplus. The red light means an overshot condition (ecological deficit) and a decreasing trend in the ecological surplus or an increasing trend in the ecological deficit. The yellow light falls in between the two conditions mentioned above (Table 2).

Table 2. Evaluation of the sustainability of NRRs in China from 2000–2010.

Status of Sustainability	Per Capita Ecological Surplus (Deficit) of 2000	Per Capita Ecological Surplus (Deficit) of 2010	Changes Of Per Capita Ecological Surplus (Deficit)	Numbers	Sum	Percentage (%)
Green light	ecological deficit	ecological surplus	ecological deficit changed into ecological surplus	1	51	15.99
	ecological surplus	ecological surplus	Increase of ecological surplus	50		
Yellow light	ecological surplus	ecological surplus	Decrease of ecological surplus	126	144	45.14
	ecological deficit	ecological deficit	Decrease of ecological deficit	18		
Red light	ecological surplus	ecological deficit	ecological surplus changed into ecological deficit	37	124	38.87
	ecological deficit	ecological deficit	Increase of ecological surplus	87		

It was found that in the year 2010, 51 NRRs (accounting for 16.0% of the total) were in the green state (Table 2, Figure 3). These reserves presented an increasing trend in the ecological surplus or changed from an ecological deficit to an ecological surplus from 2000 to 2010. Their demand for consumption did not overload their own ecosystems in 2010, i.e., the developments in these regions were sustainable.

Of the total number of NRRs, 144 (accounting for 45.1%) were in the yellow state. The ecological surplus of 126 of these NRRs decreased over this period. Meanwhile, another 18 NRRs were characterized as having an ecological deficit, and the values of ecological deficit declined from 2000 to 2010.

Of the total number of NRRs, 124 were in the red light condition (accounting for 38.9%), which means their developments were unsustainable. Thirty-seven of these NRRs changed from ecological surplus to ecological deficit, whereas another 87 NRRs had increased values of ecological deficit. These reserves should be included at the priority concern level and should be strictly controlled in terms of population growth and the intensity of exploitation.

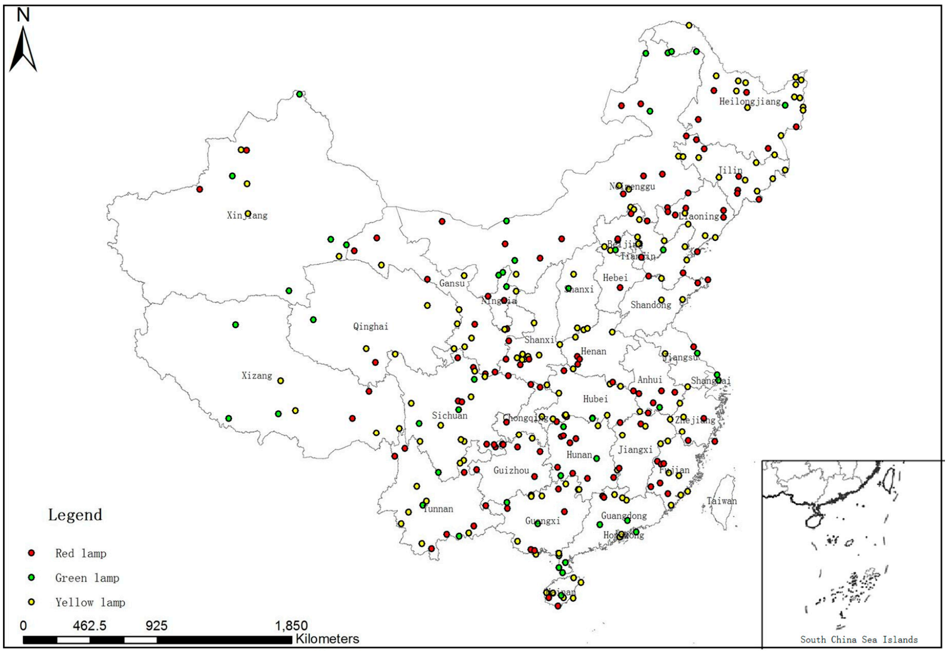

Figure 3. Sustainability (based on the 'traffic light' method) of NRRs in China from 2000–2010.

4. Discussion and Conclusions

In this study, the sustainability indices of China's 319 national nature reserves were evaluated and analyzed using the EF-based method. The results indicated that the per capita EF of all national nature reserves increased 85.86% from 2000 to 2010. Meanwhile, the per capita ecological carrying capacity of all national nature reserves increased slightly, with a rate of increase of 1.79%. The 'traffic light' method has been adopted to identify the sustainability status of those national nature reserves. It is worth noting that currently (2010) 45% of the NRRs were in the condition of ecological deficit. In terms of the dynamic changes in EF and CC, only 16% of the NRRs were sustainable. The 124 national nature reserves that were in the red state were mainly distributed in Anhui Province, Chongqing City, Hunan, Guizhou, Fujian, Shandong Province, and Inner Mongolia. The percentages of red light nature reserves in these areas were 83.3%, 66.7%, 64.7%, 62.5%, 58.3%, 57.1%, and 56.5%, respectively (Figure 4).

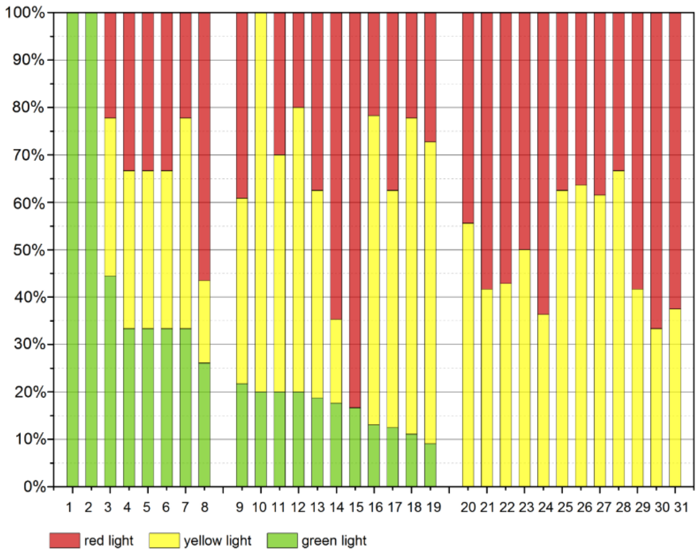

Figure 4. The proportions of nature reserves at the red, yellow, and green light states in each province.

The ecological footprint represents the critical natural capital requirements of a defined economy or population in terms of its corresponding biologically productive areas [7]. From this point of view, combined with the detailed data analysis for each NRR, the main reasons for the high proportion of red light NRRs in these regions were as follows:

(1) Increase in population. Among the 124 NRRs at the red light state, the populations of 88 NRRs (accounting for 71% of the total) showed an obviously increasing trend from 2000 to 2010. Increases in population bring forth an increasing demand for resources in the NRRs.
(2) Decrease in the per capita ecological carrying capacity. The per capita ecological carrying capacity of 62 NRRs (accounting for 50% of the total) decreased over this 10-year period. For example, the decreases in the rate of the per capita ecological carrying capacities of the Luoshan (Ningxia Province), Leigongshan (Guizhou Province), Tianhuashan (Shaanxi Province), Mangshan (Hunan Province), and Yangtze Alligator (Anhui Province) National Nature Reserves were 73.77%, 72.49%, 64.34%, 40.40%, 36.39%, respectively, mainly caused by land-use changes in these regions. In the cases in which the ecological carrying capacities were lower than the ecological footprints, the NRRs were unsustainable.
(3) Dramatic increase in ecological footprints. The per capita ecological footprints of 97.6% of the NRRs in the red light state increased from 2000 to 2010. The per capita ecological footprints of the Tongling River Dolphin National Nature Reserve (Anhui Province), the Brahmaputra Waters Canyons National Nature Reserve (Tibet), the Wolong Panda National Nature Reserve (Sichuan Province), the Xishuangbanna National Nature Reserve (Sichuan Province) and the Whooper Swan National Nature Reserve (Shandong Province) increased three times within 10 years, which indicated an improvement in the standard of living, i.e., more demand for natural resources. When the utilization of natural resources exceeds the capacity of an ecological system, the NRRs became unsustainable.

This research indicated that the EF based method might be an efficient and applicable approach for the assessment the sustainability of NRRs. The results of this study will provide more effective data for reference and for decision making support in nature reserve protection. EF accounts track one key aspect of the sustainability challenge by comparing human demand on the planet's resources with the Earth's supply of biologically productive areas. However, EF does not include the effects of pollution, loss of biodiversity, or use of water, nor does it make a distinction between natural forest and plantation. The assessment of the sustainability of certain regions of NRRs is complex and needs more intensive exploration.

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