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Research on Sustainable Development in Gansu Province Based on Three-Dimensional Energy Footprint

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Abstract. A three-dimensional (3D) energy footprint combines a 3D ecological footprint with energy theory. In this paper, based on 3D energy footprint theory, we calculated the 3D energy footprint of Gansu Province from 2001 to 2020, and quantitatively evaluated the value of the province's ecosystem services. Moreover, we also analyzed the sustainability of its ecosystem. The results show that the energy footprint of Gansu Province has been on the rise since 2001.From 2001 to 2020, only the 2015 and 2016 energy footprints in Gansu were greater than the energy carrying capacity, and the footprint depth was greater than 1, indicating that the flow of natural resources cannot meet the development needs of the province, resulting in an ecological deficit. The 3D energy footprint of Gansu Province doubled from 2001 to 2020, indicating that human use of natural resources is increasing. From the perspective of sustainable development, the development of the ecological economic system in Gansu Province only in 2015 and 2016 was not sustainable, and the development of the ecological economic system in the other years studied was sustainable.

Keywords. Three-dimensional energy footprint, Gansu Province, sustainable development

1. Introduction

With the rapid development of global economy and society, coupled with excessive development of nature by humans, the ecosystem services of the capital stock is increasingly being reduced. Since the early 1970s, numerous reports have warned that unlimited growth of the human population and consumption is not sustainable [1]. Therefore, how to achieve sustainable development of humanity and nature has become an important subject in human society. In recent years, increasingly more scholars, both in China and across the world, have conducted in-depth research on energy analysis methods, and they have proposed several sustainable development analysis methods and the corresponding calculations. Among the more influential ones are Odum's energy analysis theory [2], Ress and Wackernagel's ecological footprint method [3], and the three-dimensional (3D) ecological footprint model of Niccolucci et al. [4].

Gansu Province is located in the middle and upper reaches of the Yellow River in western China, between 32°11' and 42°57' north latitude and 92°13' and 108°46' east

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longitude. Gansu is a multi-ethnic region, its economy is dominated by agriculture, forestry, industry, animal husbandry, and tourism. On the one hand, Gansu Province's ecological environment has a significant impact on its economic development. On the other hand, the scientific assessment of regional ecosystem service value is helpful in developing scientific ecological protection plans and compensation policies [5].

The aim of this chapter is, according to the 3D ecological footprint model and on the basis of energy theory, to introduce the concept of footprint size and depth of footprint and construct a 3D energy footprint model. In addition, the sustainability of Gansu's ecosystem is analyzed.

2. Introduction to the Energy Footprint and 3D Energy Footprint

Energy theory is a new method of evaluating natural capital and ecosystem services. Emergy theory has been widely used in various fields in recent years [6-9]. Energy analysis was developed by Odum [2], and energy is defined as the energy of one type required in transformations to generate a flow and storage. The main objective of the energy footprint method is to translate human demand for natural resources and supply of natural services into comprehensible and quantifiable concepts [10].

The energy footprint model was developed by Zhao et al. [1], and it is designed to convert different types and levels of consumed energy into solar energy by the energy conversion rate, and then introduce energy density to convert the solar energy value of each project into the corresponding biological productive land area, so that the energy footprint and energy carrying capacity of a certain area can be obtained.

The calculation of the energy carrying capacity mainly considers the renewable resources in the region, such as solar radiation energy, wind energy, rainwater potential energy, rainwater chemical energy, and Earth rotation energy [10]. The energy carrying capacity can be expressed as the ratio of the total renewable energy of a region to regional energy density, and it is estimated by the following equations:

$$ec = \frac{e}{p} \tag{1}$$

$$EC = N \times ec \times 0.88 \tag{2}$$

ec is the energy carrying capacity per capita (hm^2); EC is the energy carrying capacity (hm^2); e is the renewable resources of energy amount per capita (sej); p is the earth energy density (sej/hm^2); N is the population size of a region. The final energy carrying capacity is reduced by 12% for biodiversity protection [10].

The energy footprint is estimated by the following equations:

$$p_1 = \frac{\text{total emergy of the region}}{\text{area of the region}} \tag{3}$$

$$ef = \sum_{i=1}^{n} \frac{c_i}{p_1} \tag{4}$$

$$EF = N \times ef \tag{5}$$

ef is the energy footprint per capita (hm^2); EF is the energy footprint (hm^2); c_i is the energy amount of no. i resource per capita (sej); p_1 is the energy density of a region.

Niccolucci et al. [4] proposed a 3D model of the ecological footprint, introducing footprint size and depth to represent the utilization level of human natural capital stock and flow. Based on this, we define footprint size and depth by the following equations:

$$EF_{size} = min\{EF, EC\} \tag{6}$$

$$EF_{depth} = 1 + \frac{max\{\mathrm{EF} - \mathrm{EC}, 0\}}{EC} \tag{7}$$

EF_{size} is footprint size (hm^2), and $0 < EF_{size} < EC$; EF_{depth} is footprint depth, and $EF_{depth} \geq 1$.

Then 3D energy footprint is estimated by the following equation:

$$EF_{3D} = EF_{size} \times EF_{depth} \tag{8}$$

If $EF \leq EC$, we have $EF_{depth} = 1$, indicating an ecological surplus; if $EF > EC$, we have $EF_{depth} > 1$, indicating an ecological deficit. The larger EF_{depth} is, the more natural capital stock is consumed, and the more unsustainable the development [11].

3. Calculations to the 3D Energy Footprint of Gansu Province in 2019

In this part, we analyze the ecological situation in Gansu Province by calculating its per capita energy carrying capacity, per capita energy footprint, footprint size and depth, and 3D energy footprint in 2019.

3.1. Calculations to the Energy Carrying Capacity per Capita of Gansu Province in 2019

The per capita energy carrying capacity of Gansu Province is calculated according to the Gansu Development Yearbook 2019 [12] and the energy conversion coefficient.

As can be seen from Table 1, the maximum value of the four energies is rainwater potential energy, and the sum of the per capita carrying capacity of rainwater potential energy and Earth rotation energy is 6.95 hm^2. After deducting 12% of the biodiversity protected area, the per capita energy carrying capacity of Gansu Province in 2019 was calculated as 6.12 hm^2. In 2019, the total energy of Gansu Province, the sum of rainwater potential energy and Earth rotation energy, was 5.72×10^{22} sej. The 2019 energy density of Gansu Province was $p = \frac{5.72 \times 10^{22}}{4.26 \times 10^{7}} = 1.34 \times 10^{15}\,\mathrm{sej/hm^2}$.

Table 1. The energy carrying capacity per capita of Gansu Province in 2019.

	Original data J	Energy transformity sej/J	Solar energy value sej	Per capita energy sej/cap	Per capita energy carrying capacity hm^2/cap
Solar radiant energy	2.38E+21	1.00E+00	2.38E+21	8.99E+13	2.90E-01
Wind energy	3.30E+18	6.32E+02	2.09E+21	7.89E+13	2.55E-01
Rain potential energy	4.42E+18	8.89E+03	3.93E+22	1.48E+15	4.77E+00
Chemical energy of Rainwater	1.03E+18	1.82E+04	1.87E+22	7.06E+14	2.28E+00
Energy of earth rotation	6.18E+18	2.90E+04	1.79E+22	6.77E+14	2.18E+00
Total energy of the region			5.72E+22		

3.2. Calculations to the Energy Footprint per Capita of Gansu Province in 2019

According to the Gansu Development Yearbook 2019 [12] and energy conversion coefficient, solar energy value is obtained after the conversion coefficient and energy conversion rate, and the per capita energy footprint of Gansu Province in 2019 was calculated by solar energy value; the results are presented in Table 2.

Table 2. The footprint energy per capita of Gansu Province in 2019.

Subject	**Original data/t**	**Energy transformity sej/J**	**Solar energy value /sej**	**Per capita energy /sej**	**ec /hm^2**	**Productive land type**
Wheat	2.81E+06	6.80E+04	2.64E+21	9.97E+13	7.44E-02	AL
Grain	9.23E+06	3.59E+04	5.14E+21	1.94E+14	1.45E-01	AL
Beans	3.27E+05	6.90E+05	4.67E+21	1.76E+14	1.31E-01	AL
Corn	5.94E+06	5.81E+04	5.04E+21	1.90E+14	1.42E-01	AL
Potato	2.07E+06	2.70E+03	2.35E+19	8.88E+11	6.63E-04	AL
Cotton	3.27E+04	1.90E+06	1.17E+21	4.42E+13	3.30E-02	AL
Sugar beet	2.65E+05	8.49E+04	5.62E+19	2.12E+12	1.58E-03	AL
Vegetables	1.39E+07	2.70E+04	9.42E+20	3.56E+13	2.66E-02	AL
Oil material	6.32E+05	6.90E+05	1.15E+22	4.35E+14	3.24E-01	AL
Fruit	4.39E+06	5.30E+05	8.68E+21	2.90E+14	2.16E-01	WL
Meat	1.02E+06	3.17E+06	1.49E+22	5.63E+14	4.20E-01	GL
Poultry eggs	1.51E+05	2.00E+06	1.39E+21	5.25E+13	3.92E-02	GL
Dairy	4.47E+05	1.70E+06	2.43E+21	9.18E+14	6.85E-02	GL
Wool	3.34E+04	4.40E+06	2.98E+21	1.13E+14	8.43E-02	GL
Aquatic products	1.43E+04	2.00E+06	1.32E+20	4.98E+12	3.72E-03	W
Coke	4.49E+06	3.98E+04	5.68E+21	2.15E+14	1.60E-01	FL
Gasoline	4.34E+06	5.04E+04	1.02E+22	3.85E+14	2.87E-01	FL
Diesel	5.49E+06	6.60E+04	1.20E+22	4.53E+14	3.38E-01	FL
Electric power (KWH)	1.48E+11	1.59E+05	8.47E+22	3.20E+15	2.39E+00	BL
ec/hm^2					4.88	

Note: AL, agricultural land; WL, woodland; GL, grassland; W, water area; FL, fuel land; BL, building land.

It can be seen from Table 2 that the sum of the energy footprint per capita is 8.78E-01 hm^2 for agricultural land, 2.16E-01 hm^2 for woodland, 6.12E-01 hm^2 for grassland, 3.72E-03 hm^2 for water area, and 7.85E-01 hm^2 for fuel land. The sum of the per capita energy footprint of building land is 2.39 hm^2, so the per capita energy footprint of the six land types has the following relationship: ef (building land) > ef (agricultural land) > ef (fuel land) > ef (grassland) > ef (woodland) > ef (water area). In Gansu Province, the energy footprint per capita in 2019 was equal to the sum of the energy footprint per capita of all of the projects in the six land categories, which is 4.88 hm^2.

From the Gansu Development Yearbook 2019 [12], the number of permanent residents in Gansu Province in 2019 was 2,6372,600. According to equations (4)-(8), the energy footprint of Gansu Province in 2019 is 1.29E+08 hm^2, and the energy carrying capacity of Gansu Province in 2019 is 1.63E+08 hm^2. Therefore, the footprint size of Gansu Province in 2019 is 1.29E+08 hm^2 and the footprint depth is 1; the 3D energy footprint, then, is 1.29E+08 hm^2.

4. Analysis of the Sustainability of Gansu's Ecosystem from 2001 to 2020

According to equations (1)-(8), the energy carrying capacity, energy footprint, footprint size and depth, and 3D energy footprint of Gansu Province from 2001 to 2020 are shown in Table 3.

Table 3. 3D energy footprint (EF_{3D}) of Gansu Province from 2001 to 2020.

Time	EF_{3D}/hm^2	Ecological status	Time	EF_{3D}/hm^2	Ecological status
2001	5.98E+07	Surplus	2011	1.19E+08	Surplus
2002	7.21E+07	Surplus	2012	1.19E+08	Surplus
2003	6.24E+07	Surplus	2013	1.14E+08	Surplus
2004	8.11E+07	Surplus	2014	1.31E+08	Surplus
2005	7.76E+07	Surplus	2015	1.41E+08	Deficit
2006	8.89E+07	Surplus	2016	1.40E+08	Deficit
2007	8.26E+07	Surplus	2017	1.24E+08	Surplus
2008	9.41E+07	Surplus	2018	1.21E+08	Surplus
2009	1.06E+08	Surplus	2019	1.29E+08	Surplus
2010	1.06E+08	Surplus	2020	1.36E+08	Surplus

As can be seen from Table 3 and Figure 1, since 2001, the energy carrying capacity of Gansu Province has fluctuated slightly every year, and the energy footprint, footprint size, and 3D footprint have all exhibited an overall upward trend, while the footprint size is almost unchanged. Energy carrying capacity reached the minimum value in 2002 and the maximum value in 2018, with an increase of 36% compared with 2002. The energy footprint showed fluctuating growth from 2001 to 2020, with the minimum value in 2001 and the maximum in 2015, with an increase of 136% compared with 2001. The footprint depth was the minimum in 2001 and reached the maximum in 2016, with an increase of 129% compared with 2001. The maximum footprint depth was 1.044 and the minimum was 1. The 3D energy footprint of Gansu Province doubled from 2001 to 2020, indicating that human use of natural resources is increasing.

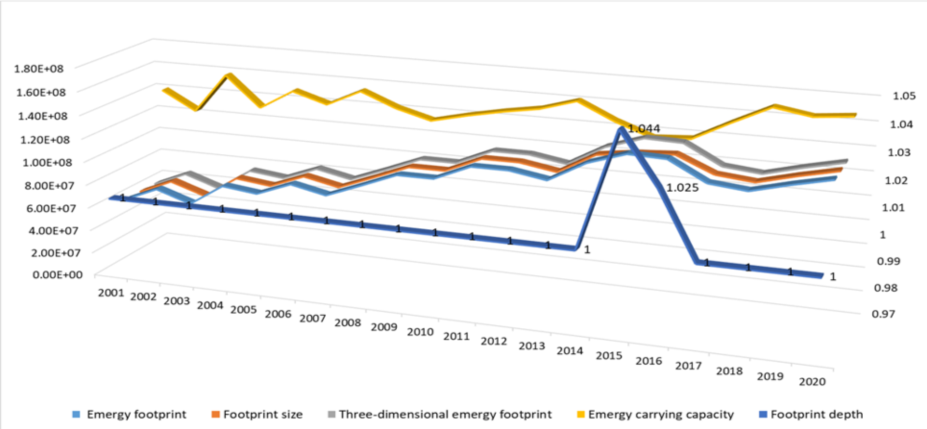

Figure 1. The plot brings to the light the changes of energy carrying capacity, energy footprint, footprint size, footprint depth and 3D energy footprint of Gansu Province from 2001 to 2020.

5. Conclusions

In this paper, the concept of footprint size and depth is introduced on the basis of energy theory, and the 3D ecological footprint model is established to analyze the ecosystem sustainability in Gansu Province.

The results show that the energy footprint of Gansu Province has been on the rise since 2001 because of the continuous development of productivity driving the development of the ecological economy. From 2001 to 2020, only the 2015 and 2016 energy footprints in Gansu were greater than the energy carrying capacity, and the footprint depth was greater than 1, indicating that the ecological economic development of Gansu Province has exceeded the range that the ecosystem can bear, and the flow of natural resources cannot meet the development needs of the province, resulting in an ecological deficit. The natural capital stock must be consumed and utilized. From the perspective of sustainable development, the development of the ecological economic system in Gansu Province in 2015 and 2016 was not sustainable, and the development of the ecological economic system in the other years studied was sustainable.

A major advantage of energy analysis is the possibility of measuring resource use of ecosystems. However, on one hand, the complexity of ecosystems makes calculations of transformities difficult and uncertain, and on the other hand, the dynamic nature and complexity of ecosystems make it likely that the measures of the value of ecosystem services will continue to be partial and incomplete. The results show that it is significant for the valuation of ecosystem services to consider various interdisciplinary study.

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