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Research Article

Ecological Footprint Analysis Applied to a Coal-Consumption County in China

Sustainable development is a critical issue in developing countries, especially for some regions whose economy depends greatly on non-renewable resources. The ecological footprint is a measured area-based indicator to analyze the sustainable use of natural resources. It has been widely used to evaluate whether the natural ecosystem's carrying capacity in a region could support its development. In this study, the method was utilized to determine the per capita ecological footprint, biocapacity and related indices for Shenmu County. Results showed that the ecological deficit was 20.075 ha/capita (cap) in 2009, indicating that Shenmu County was practicing unsustainable development, both socially and economically, and was over-exploiting its natural resources and the environment. The ecological deficit worsened between 2004, when it was "overloading" (1.978 ha/cap), and 2009, when it was "seriously overloading" (20.075 ha/cap); this was linked to increases in the ecological footprint. The main reason for the ecological deficits was the large energy consumption of industrial production. Most coal consumption was used to produce coke, and coke output thus had that greatest impact on deficits as indicated by stepwise multiple linear regression. In order to decrease ecological deficits, attention should focus on the development of alternative energy sources or technology. Improving and changing land use and energy-consumption patterns to create a resource-saving approach would result in steady increases in resource conservation leading to sustainable consumption that will improve the future ecological environment of Shenmu County.

Keywords: Biocapacity; Ecological deficit; Ecological secure; Energy footprint; Sustainability

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1 Introduction

As a typical example of a resources-consuming entity based on coal mining, the economy of Shenmu County in Shaanxi Province, China, has been booming since the late 1980s. In 2009, the coal production of Shenmu County was over 100 million tons per year, making it the largest county producer of coal in China. At present, China relies on coal for about 70% of its energy supply [1] and, therefore, coal mining in Shenmu County is of vital importance to China's economy and development. However, coal mining has not only resulted in land subsidence, lowered groundwater tables, declines in vegetation and desertification but also has the potential to cause other ecological disasters such as earthquakes and to affect river flow due to changing water use patterns in Shenmu County and neighboring areas [2]. These negative effects on the environment adversely affect the sustainable development of Shenmu County because coal is a non-renewable resource and coal mining will become economically unviable in the county in the future [3]. In China, dozens of cities in which coal mining has been carried out for more than 60 years have been confronted by the problems of economic transition and sustainability due to the depletion of their coal resources. These cities include Datong in Shanxi Province [4], Fuxin in Liaoning Province [5], and Wuhai in the Inner Mongolia Autonomous Region [6]. Therefore, to avoid the same predicament, it is essential to evaluate the sustainable use of the natural resources in Shenmu County.

Sustainability is an issue of the present age and involves finding solutions to numerous diverse environmental and social problems [7, 8]. The concept of sustainability is to attain and maintain coupled human-environmental systems in a desirable state for succeeding generations according to a society's ability, taking into account anthropogenic and environmental disturbances and uncertainties [9]. To evaluate the challenges of sustainability, different methods have been devised that define sustainable development at any scale, from a local site (e.g. a household or a biological community) to the entire globe, and that focus on the dynamic interactions between society and nature [10]. Such an integrated method is the ecological footprint (EF), which analyzes the relationship between development and environmental impacts [11]. Introduced by Rees [12], it was further developed by Wackernagel and Rees [13] to be a measure of the sustainability of a given population's consumption. The EF is defined as the total area of ecologically productive land (forests, cropland, pasture, built-up areas, and aquatic land) required to produce the resources and services consumed by a given population (ranging from

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Abbreviations: **BC**, biocapacity; **cap**, capita; **EF**, ecological footprint single individual to a whole region or country), as well as to assimilate wastes. Sustainability in a given region is assessed by comparing the land area of EF with the actual available land area, which is referred to as the biocapacity (BC). The BC is related to carrying capacity, which is defined as the maximum population of a particular species that a given region can support without irreversibly compromising its ecological productivity. If the EF of humans in a given region is larger than the BC, the region has an ecological deficit, which indicates that human consumption exceeds the capacity of the region to provide that level of consumption, i.e. the situation in the region is unsustainable. If the BC of a region is larger than the EF, the region has an ecological surplus, indicating that human activities in the region are sustainable [14]. Over the past 20 years, scientific studies on this topic have become increasingly prolific [15–17]. Based on the key formula of Wackernagel and Rees [13] along with some improvements for standardizing EF calculations, most EF analyses have been applied to various ecosystem services sustaining the population's consumption in different countries, and to identify where it exceeds the ecological source- and sink-capacity at various scales. At the national scale, the EF accounts are currently produced for more than 150 nations, with multiple calculations available for some countries [18, 19], e.g. Wiedmann et al. [20] used input–output analysis to allocate the existing EF accounts of the United Kingdom to individual consumption categories. At the regional scale, Pulselli et al. [21] showed how different methods, including EF calculations, could be integrated in order to provide an evaluation of environmental sustainability. Huang et al. [22] evaluated regional ecological security assessments based on long periods of EF analysis. At the local (city/community) scale, the Stockholm Environment Institute and others have determined the EFs of 29 cities in the European Baltic Sea area [23, 24]. Doughty and Hammond [25] also analyzed cities and sustainability within a collaborative environment research context. EF has also been applied at the even smaller scales of an urban estuary [26], industry, institute, or product, e.g. wine [27], university campus [14], and tourism [28], or at individual and household levels [29].

However, there is little evidence in the literature that the EF method was used to analyze the ecological development at a county level where the economy was based on fossil energy-consumption, and especially not in China where the economic boom is dependent on the exploitation of its coal resources. Therefore, this study uses the EF model to analyze the EF structure, to evaluate the economic development situation in a county (Shenmu County) in China where the main product is coal, and to explore the sources of ecological pressures. The purpose is to better understand the socio-economic development of the county, and to provide an example for other Chinese cities or counties where the economy is based on fossil energy-consumption in order to find a way to exploit coal while sustaining the rest of the components of the county – ecology, society. This study will contribute new information about the applicability of the ecological footprint model to a special geographic location.

2 Materials and methods

2.1 General description of Shenmu County

Shenmu County covers an area of 7635 km^2, is situated in the north of Shaanxi Province, China (109°40′ to 110°54′E, 38°13′ to 39°27′N), and is noted for its special environmental conditions due to a number of transition zones within it (Fig. 1). The county has a semi-arid continental climate with a mean annual temperature of 8.5°C; the monthly mean temperature ranges from −9.6°C in January to 23.5°C in July. The mean annual precipitation is 440 mm, about 75% of which occurs between June and September. It is in the center of the cropping-pastoral ecotone. The agricultural areas are seriously affected by sandy desertification, since the county is in the transitional zones between an aeolian deflation desert (the Mu Us Desert) and the loess hilly area of the Loess Plateau, and between arid and semi-arid areas. In the north, sandy and flat land comprises 51% of the total area of the county while hilly land in the south covers the remaining 49%. Due to these transitional characteristics and low vegetation coverage, severe soil erosion by both wind and water can occur and the natural environment is vulnerable.

Shenmu County has abundant mineral resources, such as coal, quartz, natural gas, petroleum, iron ore, and limestone. Coal resources, in particular, are vast. The demonstrated coal reserves are currently >50 billion tons and lie under an area of >4500 km^2. Large scale exploitation of the coal resources began in the late 1980s and coal mining became one of the county's main industries. Shenmu is now the largest county producer of coal (over 1.6 billion tons in 2010) and is among the top 100 gross domestic products (GDP)-producing counties (ranked 36 in 2011) in China. Since China's economy is highly dependent on coal consumption, coal mining will continue to be built up in the future. The 12th five-year Plan has allocated a target for coal production of >2.2 billion tons per year by 2015 for Shenmu County.

2.2 Models of ecological footprint and biocapacity

The formulae for determining the ecological footprint and biocapacity are [13]:

$$\mathrm{EF} = N\,\mathrm{ef} = N\sum_{i=1}^{n}\left(\frac{c_{\mathrm{i}}}{p_{\mathrm{i}}}r_{\mathrm{j}}\right) \tag{1}$$

$$\mathrm{BC} = N\,\mathrm{bc} = N\sum_{j=1}^{6}(a_{\mathrm{j}}r_{\mathrm{j}}y_{\mathrm{j}}) \tag{2}$$

where EF is the total ecological footprint (ha), N is the human population of a region (Shenmu County), ef is the mean EF per capita

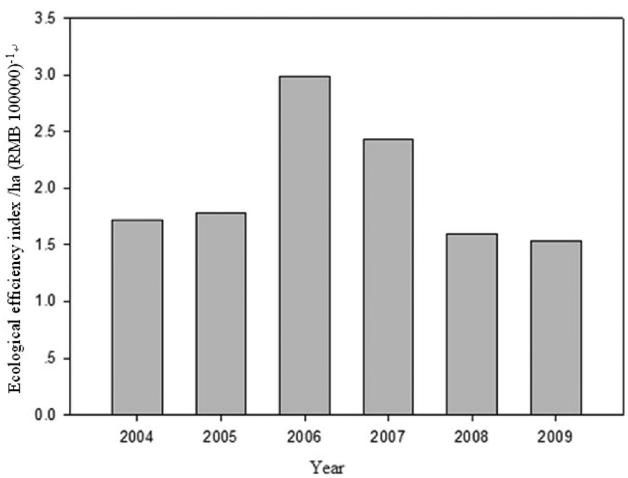

Figure 1. The ecological efficiency index, which is the energy footprint per RMB 10 000 of industrial output for the years 2004–2009.

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of a region (ha/cap), i is the consumption item category, c_i is the amount of consumption per capita of the ith item, p_i is the mean productivity of the ith item, BC is the total of biocapacity of the region (ha), bc is the biocapacity per capita, j is the biological productivity land category, a_j is the biological productive area of the jth land category, r_j is the equivalence factor of the jth land categorycategory, y_j is the yield factor of items of jth land category. In EF analysis, six main categories of biological productivity lands are defined: cropland, pasture, forest, aquatic, built-up areas, and energy, so j can have a value between 1 and 6.

2.3 Calculation of ecological efficiency

The EF can be applied to calculate the efficiency of using resources in terms of the economic gain in terms of the local currency. Therefore, for studies in China, it is often convenient to express this efficiency in units of the EF per 10 000 RMB GDP [30]. Alternatively, GDP may be substituted by industrial output. The ratio of EF to GDP or to industrial output provides an index for an ecological economic assessment that analyzes development capacity, which can reflect the utilization intensity of land resources and the efficiency of biological land use in a region, i.e. the ecological efficiency. The lower the value of the index, the higher the land productivity, the efficiency of resource use, and the ecological efficiency will be.

2.4 Gray relational analysis and multiple stepwise regressions

SPSS (11.5) was used for the following statistical analyses. Gray relational analysis may be applied to problems in order to find a reasonable solution when information is not complete. It uses a gray scale where black represents a total lack of information and white means that all the information is present while the shades of gray indicate some information is not available. Gray relational analysis was used to calculate the gray relational coefficient from the data, and then the gray relational degrees were calculated to reflect the correlations between the energy footprint and the main industrial production categories. Multiple stepwise regression was used to identify the main products that significantly affected per capita EF. Details of the gray relational analysis method can be found in Luo and Xu [31].

2.5 Data sources

The sources of data of this study were mainly the annual Statistic Yearbooks of Shenmu County (2004–2009) and the Shenmu County Annals, which were compiled from data provided from the relevant departments of the local government. Those collected data mainly included the majority of data needed to calculating EF and BC, for example, land use cover and change, the percentage distribution and consumption characteristics of the biotic resources (e.g. food, oil, vegetables, and so on) and the energy resources (e.g. coal, coke, gasoline, diesel, and so on).

3 Results and discussion

3.1 Ledgers of biotic resources and energy

To determine the EF of Shenmu County, it was first divided into two parts or ledgers: the biotic resources ledger and the energy ledger. The biotic resources ledger includes food, oil, vegetables, fruit, pork, beef, mutton, dairy (milk and goat milk), goat hair, sheep wool, cashmere, egg, fish and timber. To calculate the area of the biotic resources, the global mean yields were obtained from the United Nations Food and Agriculture Organization for 1993 (Tab. 1). The energy ledger includes coal, coke, gasoline, diesel, kerosene, coke oven gas, fuel oil, heating power, and electricity. To calculate the energy footprint, the statistical data of consumed energy were converted into units of energy land using the international average mean heat productivity criterion of unit fossil energy land area (Tab. 2).

3.2 Equivalence and yield factors

In order to make reasonable comparisons among the different types of bio-productivity areas, the EF model uses equivalence and yield factors. Equivalence factors represent the world mean potential productivity of a given bio-productive area relative to the world mean potential productivity of all bio-productivity areas. According to the Living Planet Report 2006 (World Wildlife Fund International, www.foot-printstandards.org) available in 2008 and published studies [32, 33], the equivalence factors of cropland, pasture, forest, fishery, built-up areas and energy land were 2.8, 0.5, 1.1, 0.2, 2.8, and 1.1, respectively.

The yield factor is the ratio between the national (or local) mean yield and the world mean yield for the product of one land type according to its relative productivity. In this study, estimates of the yield factors of cropland and built-up areas for 2004–2009 were based

Table 1. Global mean yields of the biotic resources present in Shenmu County

Item	Global mean yield (kg/ha)
Food	2744
Edible oil	1856
Vegetables	18 000
Melons	18 000
Fruit	3500
Pork	74
Beef	33
Mutton	33
Dairy	502
Goat hair	15
Sheep wool	15
Cashmere	15
Egg	400
Fish	29
Wood (m^3)	1.99

Table 2. Conversion coefficients for the energy ledger of the ecological footprint

Consumption category	World average energy footprint (GJ/ha)	Conversion coefficient (GJ/t)
Coal	55	20.934
Coke	55	28.470
Gasoline	93	43.124
Diesel	93	42.705
Kerosene	93	43.124
Coke oven gas	93	18.003
Fuel oil	71	50.200
Heating power (10^6 kJ)	1000	29.344
Electricity (10^4 kWh)	1000	11.840

on the official statistics for Shenmu County (Tab. 3). In contrast, the yield factors of pasture (0.91), fishery (1.00), and forest (0.19) were based on the published EF calculations for China in 1999 [32].

3.3 Analysis of the ecological footprint and biological biocapacity in 2009

3.3.1 Ecological footprint

Since local agricultural products are the main source of trade within Shenmu County and the import of other regions' agricultural products is comparatively rare, the biotic resources consumption was calculated without a trade adjustment. Table 4 shows the biotic resources ledger for Shenmu County in 2009. Cropland is clearly the largest contributor to the biological productive area while fishery is the lowest contributor. Table 5 shows the energy ledger of Shenmu County in 2009. As expected, coal consumption was the largest contributor to the biological productive area among all the energy categories.

Table 6 shows the per capita EF of Shenmu County in 2009. The total per capita EF was 21.508 ha/cap and fossil energy accounted for 93.81% of it. In the energy ledger, the contribution of coal consumption to the biological productive area was about 96.48%, which implied that coal consumption contributed 90.51% to the total per capita EF. This was to be expected since the economic development of Shenmu County has depended greatly on coal development since 1989. This was especially so from 2000, when the development and productivity of the coal mining industry increased greatly, so that by 2009 over 100 million tons of coal per year were

Table 3. Yield factor values

Yield factor	Land type					
Year	Cropland	Forest	Pasture	Fishery	Fossil fuel	Built-up land
2004	1.23	0.91	0.19	1.00	0.00	1.23
2005	1.25	0.91	0.19	1.00	0.00	1.25
2006	1.05	0.91	0.19	1.00	0.00	1.05
2007	1.31	0.91	0.19	1.00	0.00	1.31
2008	1.16	0.91	0.19	1.00	0.00	1.16
2009	1.31	0.91	0.19	1.00	0.00	1.31

Table 4. The per capita biological productive area biotic resources ledger for 2009

Category	Total output (t)	Per capita output (kg/cap)	Yield (global average) (kg/ha)	Biological productive area (ha/cap)	Land type
Food	136 113	334.799	2744	0.122	Cropland
Oil	3058	7.522	1856	0.004	Cropland
Vegetables	7225	17.771	18 000	0.001	Cropland
Melons	8167	20.089	18 000	0.001	Cropland
Fruit	22 390	55.073	3500	0.016	Forest
Pork	9983	24.555	74	0.332	Pasture
Beef	1629	4.007	33	0.121	Pasture
Mutton	9360	23.023	33	0.698	Pasture
Dairy	15 730	38.691	502	0.077	Pasture
Goat hair	202	0.497	15	0.033	Pasture
Sheep wool	1032	2.538	15	0.169	Pasture
Cashmere	250.02	0.615	15	0.041	Pasture
Egg	5040	12.397	400	0.031	Pasture
Fish	387	0.952	29	0.033	Fishery

Table 5. The per capita biological productive area of the energy ledger for 2009

Category	Consumption (t)	Global mean energy footprint (GJ/ha)	Conversion coefficient (GJ/t)	Biological productive area (ha/cap)	Land type
Coal	18 903 822	55	20.934	17.698	Fossil energy
Coke	479 942	55	28.470	0.611	Fossil energy
Gasoline	1395.53	93	43.124	0.002	Fossil energy
Diesel	28416.86	93	42.705	0.032	Fossil energy
Heating power[a)]	777 718	1000	29.344	0.056	Fossil energy
Electricity[b)]	490 587	1000	11.840	0.014	Built-up land

[a)] The unit of heating power is 10^6 kJ.
[b)] The unit of electricity is 10^4 kWh.

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Table 6. The per capita ecological footprint of Shenmu County in 2009

Land type	Biological productive area (ha/cap)	Equivalence factor	The per capita ecological footprint (ha/cap)	Percentage
Cropland	0.128	2.8	0.359	1.67
Forest	0.016	1.1	0.017	0.08
Pasture	1.502	0.5	0.751	3.49
Fishery	0.033	0.2	0.007	0.03
Fossil energy	18.343	1.1	20.177	93.81
Built-up areas	0.070	2.8	0.197	0.92
Total per capita ecological footprint			21.508	100.00

mined. The County's industrial system was thus based mainly on coal production/consumption and related industries, such as electrical power generation, the chemical industry, and the building trade. Based on the Statistic Yearbook in 2009, about 87% of GDP was attributable to industrial development in Shenmu County.

It is necessary to point out that, although a large amount of coal consumption occurred within Shenmu County, most of the products produced through that consumption were exported to other places inside China. For example, >90% of the coke and generated electricity produced by coal consumption was transported to eastern and southern regions of China such as Shanghai, Guangdong, and Jiangsu Provinces for their industrial development. This indicated that Shenmu County made contributions to other regions' economic development through the output of the products of high energy consumption. Nevertheless, the ecological burden caused by the coal mining and coke production, such as pollution, lowered groundwater tables, and declines in vegetation, fell on the County [3].

When only the non-industrial energy consumption was considered to calculate the EF of Shenmu County, the values of the per capita EF decreased from 21.508 to 1.342 ha/cap (Tabs. 7 and 8). In this case, the combined contribution of cropland and pasture would account for 82.69% of the total per capita EF. Among the six categories, pasture was the largest contributor to the EF, which and accounted for 55.96% of it. This was because Shenmu County is located in the transitional grassland between the warm-temperate and temperate zones, which makes it suitable for growing forage and the development of herbivorous animal husbandry. During the past 20 years, when the economy of Shenmu County developed rapidly, the demand for meat and poultry greatly increased with the improvement in the people's living standards. Thus, local government promoted the development of animal husbandry to meet these demands of the local people.

3.3.2 Biocapacity

Energy land is for the sequestration of CO_2 released by fossil fuel combustion. Since no such land is used exclusively for this purpose in Shenmu County, the energy land area was taken to be zero in this study. In addition, in keeping with the World Commission on Environment and Development standards, 12% of the total biocapacity was reserved for biodiversity conservation. Table 9 presents the per capita biocapacity of Shenmu County in 2009.

The per capita biocapacity of Shenmu County was 1.433 ha/cap in 2009. The structure of the per capita biocapacity was similar to that in

Table 7. The energy ecological footprint account

	Consumption (t)			The per capita ecological footprint (ha/cap)			
	Industrial	Non-industrial	Total	Industrial	Non-industrial	Total	Percentage
Coal	18896128.00	7694	18903 822	19.460	0.008	19.468	96.48
Coke	479942.00	0.00	479 942	0.672	0.000	0.672	3.33
Gasoline	165.57	1229.96	1395.53	0.000	0.002	0.002	0.01
Diesel	27297.46	1119.4	28416.86	0.034	0.001	0.035	0.17
Total				20.166	0.011	20.177	100.00
Percentage				99.94%	0.06%	100.00%	

Table 8. The per capita ecological footprint of Shenmu County based on the non-industrial energy consumption

Land type	Biological productive area (ha/cap)	Equivalence factor	The per capita ecological footprint (ha/cap)	Percentage
Cropland	0.128	2.8	0.359	26.73
Forest	0.016	1.1	0.017	1.29
Pasture	1.502	0.5	0.751	55.96
Fishery	0.033	0.2	0.007	0.49
Fossil energy	0.01	1.1	0.011	0.84
Built-up areas	0.070	2.8	0.197	14.69
The per capita ecological footprint			1.342	100.00

Table 9. The per capita biocapacity of Shenmu County in 2009

Land type	Biological productive area (ha/cap)	Equivalence factor	Yield factor	The per capita biocapacity (ha/cap)	Percentage
Cropland	0.260	2.8	1.31	0.953	58.55
Forest	0.446	1.1	0.91	0.446	27.41
Pasture	0.947	0.5	0.19	0.090	5.52
Fishery	0.048	0.2	1.00	0.010	0.58
Built-up areas	0.035	2.8	1.31	0.129	7.94
Total area				1.628	100.00
Biodiversity conservation				0.195	12.00
The per capita biocapacity				1.433	88.00

other parts of China [34]. Cropland was the largest contributor to the biocapacity, accounting for 58.55% of the total biocapacity. Forest was the second largest contributor and accounted for 27.41% of the total biocapacity. Forested areas have increased in Shenmu County due to projects based on the government policy of converting arable land that is unsuitable for cultivation to forest. Since 1999, a large-scale afforestation project has been implemented and great numbers of trees and shrubs (such as *Platycladus orientalis*, *Salix mongolica*, *Caragana korshinskii*, *Pinus tabuliformis*, and *Populus simonii*) have been planted in Shenmu County [35]. This project is not without problems since the environmental resources of the County are insufficient for such large scale planting of these species of trees and shrubs due to their higher consumption of the limited water resources and the decline in soil physical properties [36]. Consequently, the local government has changed the policy of planting forests to establishing grassland instead during the past 2–3 years. The change in policy should affect the future contribution of pasture to the biocapacity. However, in 2009, pasture accounted for only 5.52% of the total biocapacity, which is an order of magnitude below the EF requirement of pasture as calculated by the non-industrial energy consumption (Tab. 8). One possible reason for this is that the yield factor of pasture, which used the national Chinese value, could be too small. Another possible reason is that the local farmers may have been discouraged from planting pasture, due to restrictions on grazing that were intended to address the problem of over grazing, so that the area of such pastures has declined during the past ten years.

3.3.3 Ecological deficit/surplus

Table 10 shows the calculated ecological deficits and surpluses based on total energy consumption and non-industrial energy consumption. The results show that the ecological deficit was 20.075 ha/cap when calculated with total energy consumption, while there was a small ecological surplus when the calculation used non-industrial energy consumption. This indicated that the ecological demand greatly exceeded the ecological supply in Shenmu County in the former case and that the ecological pressure was mainly due to the high industrial energy consumption. The large difference between EF and BC showed that Shenmu County is a resource-consuming economic entity that is currently engaged in unsustainable development, both socially and economically, of the natural resources and the environment. Therefore, it is necessary to reduce the energy consumption in order to decrease the ecological deficit. At present, the economic development of Shenmu County is mainly dependent on the secondary industries linked to the high-energy consumption. Future industrial development should seek to utilize new high-tech industries to reduce the rate of energy dissipation thereby decreasing energy consumption.

Fishery and especially pasture land types also had ecological deficits. Shenmu County adjoins the Inner Mongolian Autonomous Region where raising sheep for wool and mutton has been historically one of the main livelihoods. With the improvement in living standards, the demand for mutton has greatly increased and the expansion of mutton production has resulted in the higher EF of pasture. However, as alluded to in Section 3.3.2, the increased sheep numbers caused severe destruction of grassland due to over grazing necessitating grazing restrictions that involved the use of enclosures and confined feeding. These restrictions in turn increased the cost of raising sheep and farmers became reluctant to maintain old, or to plant new, pastures resulting in decreases in these areas during the past ten years. Similarly, the biocapacity of pasture cannot meet the demands of the local people. To resolve this situation, Shenmu County should adjust the structure of land use to increase the amount of pasture and this can only be done by

Table 10. The ecological deficits and surpluses in Shenmu County in 2009

	Calculation with total energy consumption			Calculation with non-industrial energy consumption		
Land type	The per capita ecological footprint (ha/cap)	The per capita biocapacity (ha/cap)	The per capita ecological deficit (−)/surplus (ha/cap)	The per capita ecological footprint (ha/cap)	The per capita biocapacity (ha/cap)	The per capita ecological deficit (−)/surplus (ha/cap)
Cropland	0.359	0.953	0.594	0.359	0.953	0.594
Forest	0.017	0.446	0.429	0.017	0.446	0.429
Pasture	0.751	0.090	−0.661	0.751	0.090	−0.661
Fishery	0.007	0.010	0.003	0.007	0.010	0.003
Fossil energy	20.177	0.000	−20.177	0.011	0.000	−0.011
Built-up areas	0.197	0.129	−0.068	0.197	0.129	−0.068
Total	21.508	1.433[a]	−20.075[a]	1.342	1.433[a]	0.091[a]

[a] Those data are <12% biodiversity protection area of ecological carrying capacity.

reducing the area of cropland and/or forest. As noted in Section 3.3.2, the local government has already changed the policy of converting existing arable land that was unsuitable for cultivation to forest, which increased environmental pressures, to one that creates grassland. Continuing this policy and reducing the area of unsuitable forests would increase the biocapacity of pasture and decrease its ecological deficit in the future.

3.4 Evaluating sustainable development in Shenmu County using a time series (2004 to 2009)

The EF model is usually a static model, considering a situation at one point in time. In order to overcome this deficiency, a time series may be used to investigate the dynamics of the factors involved in the EF model [37, 38]. This study used the times series from 2004 to 2009 in order to evaluate the sustainable development of Shenmu County by analyzing the EF, biocapacity, and ecological deficit/surplus in each of these years.

3.4.1 Ecological footprint from 2004 to 2009

Table 11 shows the per capita EF, biocapacity and ecological deficit/surplus of Shenmu County from 2004 to 2009. It clearly shows that the EF of Shenmu County increased 5.2 times from 3.468 ha/cap in 2004 to 21.508 ha/cap in 2009. The largest incremental increase was 7.616 ha/cap, which occurred between 2005 and 2006 and that was mainly due to the increase in the contribution of fossil energy (5.491–13.120 ha/cap). The increase was due to the implementation of the 11th five-year plan whereby Shenmu County became one of the top 100 coal producing counties. The contributions to the EF of pasture and fishery also tended to increase during this period. The increases reflected the increasing demand for aquatic, dairy, and meat products of the people whose incomes were improving. In contrast, the cropland EF was relatively constant except for a notable decrease in 2006. The EF of forest in 2007 was notably greater than in other years because of an increase in wood consumption in that year. The EF of built-up areas generally increased, the exception being the decrease in 2009. This was due to increases in the construction of housing, infrastructure and roads that occurred as part of the integrated development planning of Shenmu County.

The per capita EF of fossil energy represented the major part of the per capita EF of Shenmu County in the study period. Thus, the per capita ecological deficit resulted primarily from the energy consumption caused by industrial development. Furthermore, the proportion of the energy footprint increased from 73.7% in 2004 to 93.8% in 2009. This coincided with the development of Shenmu County as a major base for the energy and heavy chemical industry in China. The proportion of EF due to fossil energy consumption increased more rapidly between 2004 and 2006 (11.68% from 2004 to 2005, and 8.15% from 2005 to 2006), than in the final 3 years of the study period. This coincided with the changes in the energy demands of large-scale enterprises in Shenmu County, whose numbers in each year between 2004 and 2009 were 59, 170, 322, 322, 301, and 221, respectively. Growth in the number of large-scale enterprises was initially high but slowed and declined after 2007, mainly due to the adverse effects of heavy pollution on the local environment. Due to the severe impacts of the increased pollution on the quality of life and the health of the local people, the government introduced measures to utilize new technology to increase energy efficiency and to develop clean energy production, such as wind, solar and biological power, in order to reduce pollution.

3.4.2 Biocapacity from 2004 to 2009

Table 11 shows the per capita biocapacity of Shenmu County for the period 2004–2009. Compared with the per capita EF, the changes in biocapacity were much smaller. The structure and area of the various land types comprising the per capita biocapacity did not change

Table 11. The per capita ecological footprint, biocapacity and ecological deficits, and surpluses of Shenmu County from 2004 to 2009

Year	Land type	The per capita ecological footprint (ha/cap)	The per capita biocapacity (ha/cap)	The per capita ecological deficit (−)/ surplus (ha/cap)	Year	Land type	The per capita ecological footprint (ha/cap)	The per capita biocapacity (ha/cap)	The per capita ecological deficit (−)/ surplus (ha/cap)
2004	Cropland	0.356	0.987	0.631	2007	Cropland	0.337	0.992	0.655
	Forest	0.008	0.099	0.091		Forest	0.068	0.093	0.025
	Pasture	0.539	0.485	−0.054		Pasture	0.693	0.464	−0.230
	Fishery	0.003	0.000	−0.002		Fishery	0.006	0.000	−0.006
	Fossil energy	2.555	0.000	−2.555		Fossil energy	17.309	0.000	−17.309
	Built-up land	0.008	0.122	0.115		Built-up land	0.124	0.126	0.002
	Total	3.468	1.490[a)]	−1.978[a)]		Total	18.538	1.475[a)]	−17.064[a)]
2005	Cropland	0.343	0.982	0.639	2008	Cropland	0.362	0.858	0.496
	Forest	0.007	0.097	0.090		Forest	0.018	0.092	0.074
	Pasture	0.591	0.482	−0.109		Pasture	0.746	0.455	−0.290
	Fishery	0.006	0.010	0.005		Fishery	0.006	0.010	0.004
	Fossil energy	5.491	0.000	−5.491		Fossil energy	18.165	0.000	−18.165
	Built-up land	0.011	0.123	0.112		Built-up land	0.260	0.110	−0.149
	Total	6.449	1.491[a)]	−4.958[a)]		Total	19.556	1.342[a)]	−18.214[a)]
2006	Cropland	0.281	0.813	0.532	2009	Cropland	0.359	0.953	0.594
	Forest	0.007	0.096	0.089		Forest	0.017	0.446	0.073
	Pasture	0.622	0.475	−0.147		Pasture	0.751	0.090	−0.305
	Fishery	0.006	0.010	0.004		Fishery	0.007	0.010	0.003
	Fossil energy	13.120	0.000	−13.120		Fossil energy	20.177	0.000	−20.177
	Built-up land	0.028	0.103	0.074		Built-up land	0.197	0.129	−0.068
	Total	14.065	1.317[a)]	−12.748[a)]		Total	21.508[a)]	1.433	−20.075[a)]

[a)] Those data are less 12% biodiversity protection area of ecological carrying capacity.

much in this period. The overall changes in the total per capita biocapacity followed the same pattern as those of the biocapacity of cropland, which fluctuated a little during this time. Among the five contributing land uses, the proportions decreased in the order cropland > forest > built-up areas ≈ pasture > fishery, and the order remained the same between 2004 and 2009.

3.4.3 Ecological deficit/surplus from 2004 to 2009

The ecological budget was in deficit for all the years between 2004 and 2009 (Tab. 11) because the EF increased greatly while the biocapacity did not grow. The ecological deficit increased 10.15-fold from 1.978 ha/cap in 2004 to 20.075 ha/cap in 2009. This clearly indicated that the ecological sustainability situation in Shenmu County is worsening. Cropland always exhibited small surpluses. However, fossil energy always had much larger deficits that were directly related to the total ecological deficits and were the main reason for the ecological deficit of Shenmu County. Pasture exhibited deficits, albeit considerably smaller than those of fossil energy.

The results of this study showed that the ecological deficit in Shenmu County worsened from overloading (1.978 ha/cap in 2004) to seriously overloading (20.075 ha/cap in 2009). Statistics from the Shenmu Statistical Yearbook (Shenmu Bureau of Statistics, 2004–2009) showed that urbanization developed rapidly at a rate that increased from 45% (in 2004) to 62% (in 2009). This will further increase as, according to the 12th five-year plan for Shenmu, the urbanization rate will be >80% and coal production will increase to >2.2 billion tons per year in 2015. Therefore, along with this rapid development and urbanization, ecological overloading will become even more severe and will lead to unsustainable development.

3.5 Analysis of the main influencing factors of the energy footprint

The analysis of the EF of Shenmu County showed that fossil energy was the main contributor to the EF. The ecological deficit was also mainly due to fossil energy consumption. Identifying the main influencing factors of the energy footprint could facilitate control of the EF of Shenmu County and thereby reduce the ecological deficit. Therefore, gray relational analysis and multiple stepwise regressions were used to analyze the energy footprint indexes and impact factors of the energy footprint.

3.5.1 Energy footprint per RMB 10 000 industrial output

Figure 1 shows the annual energy footprint per RMB 10 000 GDP of industrial output in Shenmu County between 2004 and 2009, which reflects the efficiency of resources use. The energy footprint per RMB 10 000 initially increased from 1.726 ha (RMB 10 000)$^{-1}$ in 2004 to 2.990 ha (RMB 10 000)$^{-1}$ in 2006, which means that the efficiency of resources use decreased. In 2009, the value declined to 1.532 ha (RMB 10 000)$^{-1}$, indicating an improvement in the efficiency of resources use. This corresponded to the introduction of new technology by local enterprises in 2007.

3.5.2 Results of gray relational analysis and multiple stepwise regression

The energy footprint of Shenmu County was based on energy consumption that was mainly due to industrial production and this was also the main reason for the large ecological deficit. The Statistical Yearbook identified ten main types of industrial products, which were coal, cement, coke, magnesium, electricity, calcium carbide, plate glass, corvic, methanol, and ferroalloy. Table 12 shows the gray relational grades of these ten products and the population to the energy footprint. The gray relational grade indicates the influence of a factor on the energy footprint. Thus, the two highest gray relational grades showed that coke production (0.919) and electricity generation (0.894) had the greatest effects on the energy footprint, while the lowest value showed that ferroalloy production (0.621) had the least effect.

The results of the multiple stepwise regression analysis produced a linear regression model:

$$y = 3.348 + 3.24 \times 10^{-6}x \tag{3}$$

where y is the per capita energy footprint, and x is coke output. The coefficient of determination was 0.97, which means that the fit of the model to the data was good ($t = 12.732$, $a = 0.05$). The model indicated that the per capita energy footprint of Shenmu County was positively correlated with coke production and, since no other factors significantly improved the model, that coke was the main product directly affecting the per capita energy footprint. The other nine products were also high-energy consumers and most used coal-produced energy. However, the production of coke far outweighed them for the demand of coal-produced energy. Hence, coke as the main consumer of coal, which contributed >90% to the energy footprint (Tab. 7), was indirectly the greatest factor affecting the energy footprint.

4 Concluding remarks

The EF model is an important method for measuring the sustainable development of regions and reflects the difference between economic development and biocapacity. The model was used to assess the sustainability of development in Shenmu County and the results indicated that it could be used as an indicator for the systematic analysis related to such development.

The study enabled the following conclusions to be drawn about Shenmu County: (i) The ecological deficit had increased to 20.075 ha/cap in 2009, indicating that development in terms of society, economy, natural resources, and the environment were

Table 12. The gray relational degree of influence factors and energy footprint

Factor	Coal (10 000 t)	Cement (t)	Coke (t)	Mg (t)	Electricity (10 000 KWH)	Calcium carbide (t)
Relational degree	0.859	0.804	0.919	0.823	0.894	0.782
Factor	Plate glass (1000 t)	Corvic (t)	Methanol (t)	Ferroalloy (t)	Population	
Relational degree	0.845	0.815	0.770	0.621	0.771	

unsustainable. Coal consumption was the main reason for the ecological deficit; (ii) the ecological deficit status worsened from overloading (1.978 ha/cap) in 2004 to seriously overloading (20.075 ha/cap) in 2009 due to large increases in the EF. Due to continuing rapid development and urbanization, the ecological overload will become more severe and development will be more unsustainable; (iii) coke production, as the largest coal-power consumer, was identified as the main factor affecting the EF by both stepwise regression and gray relational analysis. The regression model showed a direct linear relationship between per capita EF (y) and coke production (x): $y = 3.348 + 3.24 \times 10^{-6}x$.

The study results showed that the economic development of Shemnu County was greatly dependent on coal consumption and coke production. This industrial structure is clearly unsustainable because of the enormous pressure it puts on the environment, as indicated by the ecological deficit and the accompanying severe pollution. Therefore, in order to have sustainable ecological systems in Shenmu County, it is necessary to consider the relationship between economic development and coal mining, the environmental effects and ways to protect it. In addition, the ecological demand-supply and sustainability of a region should be considered as important indicators when the governments are making policies for economic and urban development.

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