The Emergy-based Ecological Footprint (EEF) of Traditional Agricultural Areas in China: A Case Study of Congjiang County, Guizhou Province

JIAO Wenjun1,2, MIN Qingwen1*, CHENG Shengkui1, ZHANG Dan1 and SUN Yehong1

1 Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China; 
2 Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: Traditional agricultural systems are under severe threat from modernization, technological and economic changes, while substitution of traditional agriculture with so-called modern agriculture has caused serious non-point source pollution. Ecological footprint, though an approach to measure ecological sustainability, fails to reveal the true environmental condition of the traditional agricultural areas. This paper attempted to establish an enhanced emergy-based ecological footprint (EEF) which could include all the flows of ecosystem services that the local inhabitants had consumed, thus making EEF a better indicator of the regional sustainability. This new approach was then applied to evaluate the sustainability of Congjiang County in Guizhou Province, a typically traditional agricultural area in China. Results showed that the local biocapacity could only meet 64% of the total consumption needed by the local inhabitants, leaving an ecological deficit of 5.2327 gha per capita. This analysis was contrary to earlier findings obtained through the conventional method that Congjiang County was characterized by a small ecological reserve. Disaggregated analysis revealed that the consumption of waste treatment and erosion control services occupied a considerable proportion of the local ecological footprint, indicating that regional sustainability was under serious threat from waste discharge and soil erosion.

Key words: emergy-based ecological footprint (EEF); ecological footprint (EF); emergy; ecosystem services; sustainability assessment; traditional agricultural area

1 Introduction

Ecological footprint is introduced as a synthetic indicator for measuring the amount of natural resources and ecosystem services required to support the consumption of a specified population (Rees 1992; Wackernagel and Rees 1996). Given its simplicity and metaphor, ecological footprint has been applied in various studies and analyses in different geographical regions, spatial scales and time series (Senbel et al. 2003; Wackernagel et al. 2004; van Vuuren and Bouwman 2005; Medved 2006; Lammers et al. 2008) and has been widely acknowledged as an evaluation tool for sustainability. However, as happens with all the tools that evaluate sustainability, ecological footprint has also received a number of criticisms in its assumptions, methods and data (van den Bergh and Verbruggen 1999; Moffatt 2000; Ayres 2000; Lenzen and Murray 2001; Wiedmann and Lenzen 2007; Lenzen et al. 2007). Some of them are described in the following ones: (i) Ecological footprint only captures the primary function of an area, even if the area supplies two or more ecosystem services, in order to ensure that each area is added only once to the accounting; (ii) Not only the forest but also the ocean, cropland and pasture absorb CO2 from the atmosphere and they also need calculating in the footprint of fossil fuels, even in a low proportion confronted to forest; (iii) Ecological footprint does not include the area needed to assimilate the pollutants (except for CO2) released by human activities, such as residues of fertilizers and pesticides due to agricultural production. Nor does
it consider the area demand for side effects of human activities, such as soil erosion caused by cropland tilling; and (iv) Footprint derived from freshwater use is only indirectly accounted in the ecological footprint, which is not yet allocated to the consumer of the water resources (Kittzes et al. 2007).

Efforts to mend these deficiencies and shortcomings have led to diversified forms of ecological footprint (Bicknell et al. 1998; Barrett and Simmons 2003; Best Foot Forward 2004; Erb 2004; Zhao et al. 2005), among which ecological footprint based on emergy (hereafter EEF) is a brilliant one. Zhao et al. (2005) first introduced emergy analysis along with ecological footprint and obtained the same conclusions by using EEF and conventional ecological footprint. In this new method, biocapacity and ecological footprint per capita were obtained by respectively dividing the total emergy amount of available renewable resources and human consumption by population and emergy density. Chen and Chen (2006) further investigated EEF accounting procedures and finally made a time series study of Chinese society with improved EEF method. The authors suggested that global emergy density be used for the calculation of both biocapacity and ecological footprint, thus ensuring the final results comparable with each other. Agostinho et al. (2007) discussed the insertion of additional land demands in the calculation of ecological footprint and biocapacity for agricultural production. Siche et al. (2009) commented on the proposal of Zhao et al. (2005) to consider the biggest renewable energy flow as biocapacity and suggested to incorporate energy flows derived from the internal biomass stocks. The authors included two important categories concerning natural resources use in the EEF accounts: top soil loss and water consumption, which were not calculated within the conventional method. They also suggested that global emergy density (GED) be used to convert each category to global hectares while local emergy density (LED) correspond to obtain a footprint in local hectares.

Ecological footprint is an easy and rapid appraisal method for assessing sustainability by comparing human demand with nature’s available supply for human use. However, it fails to provide a reasonable sustainability assessment because it does not fully capture the ecosystems services that humans consume. For instance, footprints derived from fossil fuel combustion in most studies account for quite a large proportion of the total ecological footprint, especially in some typical industrialized regions where this kind of footprint represents between one and two thirds of the entire ecological footprint (Bagliani et al. 2008). But in other regions like traditional agricultural areas, fossil fuel combustion may not be a main ecological problem, while water pollution, soil erosion and salinization caused by agricultural production may be serious threats to local environment. Assessing sustainability considering these agricultural side effects is obviously beyond the capability of conventional ecological footprint. The combination of ecological footprint with emergy analysis has to some extent mended the deficiencies of conventional ecological footprint, for emergy analysis is able to analyze all kinds of resources, goods and services that humans consume, which provides the possibility of obtaining a better index of sustainability. However, most studies about EEF have not fully captured human consumptions but still been limited to the scope of conventional ecological footprint. Few studies like Siche et al. (2009) try to take into account categories concerning resources use, but EEF framework with all kinds of resources, goods and service that humans consume has not been formed yet.

In this paper we further improved the EEF method by introducing the concept of ecosystem services into the EEF framework, enabling EEF as a more reasonable and effective index of sustainability. Then we applied the enhanced EEF method to evaluate the sustainability of Congjiang County in Guizhou Province, a typically traditional agricultural area in China. In this case study, we focused on seven categories of ecosystem services that local inhabitants consumed and obtained interesting and meaningful results which were quite different from those drawn from conventional ecological footprint. Besides results comparison, contrast between methodologies of EEF and conventional EF was also conducted in this paper, aimed for better understanding of the EEF method and its further development.

2 Enhanced EEF method

Capital is generally considered as a stock of materials or information that exists at a point in time. Each form of capital stock generates, either autonomously or in conjunction with services from other capital stocks, a flow of services that may be used to transform materials, or the spatial configuration of materials, to enhance the welfare of humans (Costanza et al. 1997). The human use of this flow of services may or may not leave the original capital stock intact. From this point of view, ecological footprint is introduced to measure whether the human consumption of ecosystem services jeopardizes the intactness of the natural capital they are derived from.

2.1 The calculation of biocapacity

Given that the ecosystem services humans consume are flows of materials, energy and information from natural capital, the biocapacity should be considered as the total quantity of available flows of services the natural capital stocks provide in a given region rather than the natural capital itself. And it is believed that the flows derived from the available internal stocks can be eventually attributed to the renewable external flows like sun, wind and rain. For
this reason, we did not adopt the procedure put forward by Siche et al. (2007) but the proposal of Zhao et al. (2005) that considered the biocapacity as the biggest renewable energy flow. Five kinds of renewable resources energy were considered here: solar energy, kinetic energy in wind, chemical energy in rain, geopotential energy in rain and earth cycle energy. The energy of the five kinds of energy may be calculated in the following formula:

\[
\text{Emergy} = \text{Energy of resource (J)} \times \text{Transformity of resource (sej J}^{-1})
\]

(1)

where emergy is used to realize the conversion of energy to emergy flows. The biocapacity per capita then may be obtained through the following formula:

\[
BC_p = \frac{Em_{\text{max}}(\text{sej})}{GED(\text{sej g ha}^{-1}) \times P}
\]

(2)

where \(BC_p\) refers to the biocapacity per capita, \(Em_{\text{max}}\) is the largest renewable energy flow, GED is the global emergy density which is \(3.1E+14 \text{ sej g ha}^{-1}\) calculated by Zhao et al. (2005), and \(P\) refers to the population of the region.

2.2 The calculation of ecological footprint

As is mentioned above, we regarded the ecological footprint as the amount of flows of ecosystem services required to support the consumption of a given population. Costanza et al. (1997) grouped ecosystem services into 17 major categories. The consumption amounts of different categories of ecosystem services should be calculated in different ways. For tangible forms of ecosystem services, such as food production, raw materials and water supply, the consumption amounts could be directly accounted by measuring the quantity of food or the volume of water the inhabitants had consumed. On the other hand, the consumption amounts of intangible ecosystem services, such as gas regulation, waste treatment and erosion control, could be indirectly acquired by calculating the quantities of the associated materials consumed by the inhabitants. After translating these amounts into the common units emergy using the formula (1), the ecological footprint per capita may be obtained as follows:

\[
EF_p = \sum_{i=1}^{n} \frac{Em_i(\text{sej})}{GED(\text{sej g ha}^{-1})} \times P
\]

(3)

where \(EF_p\) refers the ecological footprint per capita, \(Em_i\) is the energy flow of the \(i\)th ecosystem service consumed, GED is the global emergy density which is \(3.1E+14 \text{ sej g ha}^{-1}\) calculated by Zhao et al. (2005), and \(P\) refers to the population of the region.

3 Study area and data preparation

3.1 The characteristics of Congjiang County

Congjiang County of Guizhou Province, a typically traditional agricultural area in China, was selected to apply the enhanced EEF method. It is situated in the Miao and Dong Minorities Autonomous Prefecture of Southeast Guizhou with an area of 3244 km\(^2\) (Fig.1). The county is mainly composed of low mountains and hills which constitute nearly 90% of the total land area. It is dominated by a mid-subtropical warm and humid monsoon climate with the average annual temperature of 18.4\(^\circ\)C and the average annual precipitation of 1193 mm. By the end of 2007, the county had 21 communes comprising a total of 294 villages and a population of 328 211, of whom 94.8% were living in rural areas. It is also a multi-ethnic area: the population of minority nationalities was about 309 531 in 2007, which accounted for 94.3% of the total population. Given some physical limits and historical reasons, Congjiang County has continued to maintain the traditional rice-fish agriculture and has formed distinctive cultural heritage based on this, thus being regarded as a
typically traditional agricultural area.

3.2 Data collection and development

The calculation of EEF required a great amount of information and both secondary and primary data were used in the calculation process. The secondary data were extracted from statistical yearbooks in 2008 and documents provided by the associated departments of the government of Congjiang County. The primary data were collected through a household survey, focus group discussions, interviews with key informants and field observations. A household survey, designed to acquire the consumption amounts of ecosystem services like waste treatment, was one of the major sources of information and was collected using a standard questionnaire. The sample size was determined on the basis of total households in the study area. First, three communes that represent the general situation of the county in terms of geographic and socioeconomic conditions as well as farming practices were selected through purposive sampling. Second, one village from each of the communes was selected according to the selection criteria. A simple random sampling method was adopted to select households for the questionnaire survey. In order to identify the total sample household population, the names of the households were taken from the registration books of the respective village. After identification of the households, they were numbered and randomly sampled. Accordingly, a total of 162 households were selected, which accounted for at least 32% of the total households of the sampled villages. The household survey was conducted from the first week of May to the second week of June, and continued from the second week of July to the third week of August in 2008.

Here we selected seven categories of ecosystem services to divide the consumption of the inhabitants of Congjiang County. Details about the calculation of the consumption amounts of these ecosystem services were elaborated as follows: (i) Food production. The components of this category were mainly primary products from agriculture and forestry and partly secondary products from animal husbandry and fishery. Agricultural products included rice, wheat, sweet potatoes, corn, potatoes, peanuts, beans, vegetables and watermelons. Fruits like oranges were calculated as forest products. To avoid double counting, husbandry products such as pork, poultry and eggs were not accounted for because pigs, chickens and ducks were usually fed with grains, however beef and mutton considered as secondary products from pasture were included. Both the fish caught from rivers and rice paddies were calculated. (ii) Raw materials. This category consisted of materials provided by the environment for human use in daily life and production, such as rapeseeds, cotton, sugar cane, feed, roundwood and fuelwood. (iii) Water supply. Water for three kinds of human uses was accounted in this category: water for industrial use, water for domestic use and water for irrigation and livestock. Most factories in the county utilized river water for production while nearly 95% of the local inhabitants used spring water in their daily life, so water for different purposes had different sources and then different emergy transformities. (iv) Gas regulation. Gas regulation is the benefit which humans derive from the ecosystem function to regulate the atmospheric chemical composition, including CO₂/O₂ balance, O₃ for UVB protection and SO₂ levels. Here only the consumption of CO₂ sequestration service of the ecosystem was taken into account and the consumption amount was indirectly measured by accounting for the amounts of the major energy resources like electricity, coal and fuel the local inhabitants consumed. (v) Waste treatment. In this category the waste was mainly referred to the residues of chemical fertilizers and pesticides caused by the agricultural production. The consumption amount of this kind of ecosystem services was obtained through the calculation of the amounts of the chemical fertilizers and pesticides the local people used. (vi) Erosion control. The consumption amount of the erosion control service was acquired by multiplying the volume of the soil lost every year by the average organic content and the energy content of the organic matter. and (vii) Biodiversity conservation. We set aside 12% of the biocapacity available to provide reserve areas for local biodiversity conservation (Wackernagel et al. 2004) and regarded this value as the amount of this kind of ecosystem services the local non-human inhabitants consumed.

The consumption categories and main data sources were reported in Table 1.

4 Results

4.1 The biocapacity of Congjiang County

The biocapacity in the EEF was considered as the total quantity of available flows of services the natural capital stocks provide in a given region in this paper. Since the flows derived from the available internal stocks could be finally attributed to the renewable external flows, the biocapacity in the EEF could be calculated as function of renewable resources in a different way from the conventional method. Table 2 showed the calculation results of the biocapacity of Congjiang County in 2007 and the raw data could be found in Appendix A. From Table 2 we could see that the geopotential energy in rain was the largest renewable emergy flow so the biocapacity of Congjiang County obtained by the EEF method was 9.3311 gha per capita in 2007.

4.2 The ecological footprint of Congjiang County

The ecological footprint in the EEF was defined as the amount of flows of ecosystem services required to support the consumption of a given population in this
Here seven categories of ecosystem services were accounted: food production, raw materials, water supply, gas regulation, waste treatment, erosion control and biodiversity conservation. Table 3 showed the footprint results of Congjiang County in 2007 using the EEF method and the calculations were presented in Appendix B. As reported in Table 3, the ecological footprint of Congjiang County was 14.5638 gha per capita in 2007.

4.3 The ecological balance of Congjiang County

The ecological footprint final value of a sub-national area cannot be significant if considered in itself, but it may offer important insights when compared with other quantities such as the biocapacity on different spatial scales. So we started our analysis by comparing the local biocapacity, which measured the available ecosystem services provided in the county, with the ecological footprint that estimated the ecosystem services demanded by the local inhabitants. The local biocapacity was able to cover 9.3311 out of the 14.5638 gha per capita of the ecological surface required by the county, which indicated that the local biocapacity could only meet 64% of the total consumption needed by the local inhabitants, leaving an ecological deficit of 5.2327 gha per capita.

4.4 The disaggregated analysis of results

When structuring the calculation of a territory’s ecological footprint and biocapacity, it is important to ensure an adequate degree of disaggregation so as to allow the analyst to derive a multiple and insightful reading of the

Table 1 The consumption categories and main data sources in the calculation EEF.

<table>
<thead>
<tr>
<th>Consumption categories</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Food production</td>
<td>Statistical Yearbook of Congjiang County 2008</td>
</tr>
<tr>
<td>- Grain (rice; wheat; sweet potatoes; corn; potatoes; beans; peanuts)</td>
<td></td>
</tr>
<tr>
<td>- Meat and fish (beef; mutton; fish)</td>
<td></td>
</tr>
<tr>
<td>- Vegetables and fruits (vegetables; watermelons; oranges)</td>
<td></td>
</tr>
<tr>
<td>2. Raw materials</td>
<td>Statistical Yearbook of Congjiang County 2008</td>
</tr>
<tr>
<td>- Wood (roundwood; fuelwood)</td>
<td></td>
</tr>
<tr>
<td>- Others (rapeseeds; cotton; sugar canes; feed)</td>
<td></td>
</tr>
<tr>
<td>3. Water supply</td>
<td>Statistical Yearbook of Congjiang County 2008 and questionnaires for fuelwood and livestock feed</td>
</tr>
<tr>
<td>- Water for industrial use</td>
<td></td>
</tr>
<tr>
<td>- Water for domestic use</td>
<td></td>
</tr>
<tr>
<td>- Water for irrigation and livestock</td>
<td></td>
</tr>
<tr>
<td>- Electricity</td>
<td></td>
</tr>
<tr>
<td>- Coal</td>
<td></td>
</tr>
<tr>
<td>- Fuel (diesel oil, gasoline and lubricants)</td>
<td></td>
</tr>
<tr>
<td>5. Waste treatment</td>
<td>Statistical Yearbook of Congjiang County 2008</td>
</tr>
<tr>
<td>- Fertilizers (phosphate; nitrogen; potash)</td>
<td></td>
</tr>
<tr>
<td>- Pesticides</td>
<td></td>
</tr>
<tr>
<td>6. Erosion control</td>
<td>Documents from the Water Conservancy Bureau of Congjiang County and questionnaires for water for domestic use and livestock</td>
</tr>
<tr>
<td>- Soil erosion</td>
<td></td>
</tr>
<tr>
<td>7. Biodiversity conservation</td>
<td>12% of available biocapacity</td>
</tr>
</tbody>
</table>

Table 2 Biocapacity of Congjiang County in 2007 calculated using EEF method.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Unit</th>
<th>Raw data</th>
<th>Transformity (sej unit⁻¹)</th>
<th>Total emergy (sej)</th>
<th>Emergy per capita (sej)</th>
<th>Biocapacity per capita (gha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar energy</td>
<td>J</td>
<td>9.43E+18</td>
<td>1.00E+00</td>
<td>9.43E+18</td>
<td>2.87E+13</td>
<td>0.0927</td>
</tr>
<tr>
<td>2</td>
<td>Rain, chemical energy</td>
<td>J</td>
<td>1.90E+16</td>
<td>3.10E+04</td>
<td>5.89E+20</td>
<td>1.79E+15</td>
<td>5.7890</td>
</tr>
<tr>
<td>3</td>
<td>Rain, geopotential energy</td>
<td>J</td>
<td>2.02E+16</td>
<td>4.70E+04</td>
<td>9.49E+20</td>
<td>2.89E+15</td>
<td>9.3311</td>
</tr>
<tr>
<td>4</td>
<td>Wind, kinetic energy</td>
<td>J</td>
<td>2.01E+14</td>
<td>2.45E+03</td>
<td>4.92E+17</td>
<td>1.50E+12</td>
<td>0.0048</td>
</tr>
<tr>
<td>5</td>
<td>Geothermal energy</td>
<td>J</td>
<td>3.24E+15</td>
<td>5.80E+04</td>
<td>1.88E+20</td>
<td>5.73E+14</td>
<td>1.8470</td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.3311</td>
</tr>
</tbody>
</table>

Note: transformity references for respective row number: 1. Definition; 2–5. See Odum et al. (2000).
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We decided to disaggregate the ecological footprint final results according to the categories of ecosystem services in order to find the contributions of the consumption categories to the final values. Fig. 2 showed the percentages of the ecological footprint of Congjiang County disaggregated according to the categories of ecosystem services. It is immediately evident that nearly half of the ecological footprint was derived from the consumption of the food production service (46%) and the second one was the consumption of the raw materials which corresponded to 18% of the total ecological footprint. It is important to point out that the sum of these categories accounts for the entire ecological footprint of Congjiang County in 2007.

Table 3 Ecological footprint of Congjiang County in 2007 calculated by the EEF method.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Unit</th>
<th>Raw data</th>
<th>Transformity (sej unit⁻¹)</th>
<th>Total emergy (sej)</th>
<th>Emergy per capita (sej)</th>
<th>Ecological footprint per capita (gha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Food production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>rice</td>
<td>J</td>
<td>1.20E+15</td>
<td>6.03E+04</td>
<td>7.24E+19</td>
<td>2.20E+14</td>
<td>0.7112</td>
</tr>
<tr>
<td>2</td>
<td>wheat</td>
<td>J</td>
<td>5.00E+13</td>
<td>1.44E+05</td>
<td>7.20E+18</td>
<td>2.19E+13</td>
<td>0.0708</td>
</tr>
<tr>
<td>3</td>
<td>sweet potatoes</td>
<td>J</td>
<td>8.44E+13</td>
<td>4.54E+04</td>
<td>3.83E+18</td>
<td>1.17E+13</td>
<td>0.0377</td>
</tr>
<tr>
<td>4</td>
<td>corn</td>
<td>J</td>
<td>1.69E+14</td>
<td>7.37E+05</td>
<td>1.25E+20</td>
<td>3.79E+14</td>
<td>1.2242</td>
</tr>
<tr>
<td>5</td>
<td>potatoes</td>
<td>J</td>
<td>1.25E+14</td>
<td>1.78E+05</td>
<td>2.23E+19</td>
<td>6.78E+13</td>
<td>0.2187</td>
</tr>
<tr>
<td>6</td>
<td>peanuts</td>
<td>J</td>
<td>4.64E+13</td>
<td>9.21E+05</td>
<td>4.27E+19</td>
<td>1.30E+14</td>
<td>0.4200</td>
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<tr>
<td>7</td>
<td>beans</td>
<td>J</td>
<td>4.86E+13</td>
<td>4.04E+05</td>
<td>1.96E+19</td>
<td>5.98E+13</td>
<td>0.1930</td>
</tr>
<tr>
<td>8</td>
<td>vegetables</td>
<td>J</td>
<td>3.10E+14</td>
<td>4.54E+04</td>
<td>1.41E+19</td>
<td>4.29E+13</td>
<td>0.1383</td>
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<tr>
<td>9</td>
<td>watermelons</td>
<td>J</td>
<td>2.71E+14</td>
<td>3.81E+04</td>
<td>1.03E+19</td>
<td>3.15E+13</td>
<td>0.1015</td>
</tr>
<tr>
<td>10</td>
<td>oranges</td>
<td>J</td>
<td>5.54E+14</td>
<td>1.09E+05</td>
<td>6.04E+19</td>
<td>1.84E+14</td>
<td>0.5935</td>
</tr>
<tr>
<td>11</td>
<td>beef</td>
<td>J</td>
<td>1.37E+14</td>
<td>8.60E+05</td>
<td>1.18E+20</td>
<td>3.59E+14</td>
<td>1.1580</td>
</tr>
<tr>
<td>12</td>
<td>mutton</td>
<td>J</td>
<td>1.34E+12</td>
<td>3.36E+06</td>
<td>4.50E+18</td>
<td>1.37E+13</td>
<td>0.0443</td>
</tr>
<tr>
<td>13</td>
<td>fish</td>
<td>J</td>
<td>3.44E+13</td>
<td>5.20E+06</td>
<td>1.79E+20</td>
<td>5.45E+14</td>
<td>1.7581</td>
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<tr>
<td></td>
<td>Raw materials</td>
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<tr>
<td>14</td>
<td>rapeseed</td>
<td>J</td>
<td>9.68E+13</td>
<td>1.16E+06</td>
<td>1.12E+20</td>
<td>3.42E+14</td>
<td>1.1036</td>
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<td>15</td>
<td>cotton</td>
<td>J</td>
<td>8.50E+11</td>
<td>1.36E+06</td>
<td>1.16E+18</td>
<td>3.52E+12</td>
<td>0.1114</td>
</tr>
<tr>
<td>16</td>
<td>sugarcane</td>
<td>J</td>
<td>6.48E+12</td>
<td>2.10E+04</td>
<td>1.36E+17</td>
<td>4.15E+11</td>
<td>0.0013</td>
</tr>
<tr>
<td>17</td>
<td>feed</td>
<td>J</td>
<td>7.92E+12</td>
<td>4.54E+04</td>
<td>3.60E+17</td>
<td>1.10E+12</td>
<td>0.0035</td>
</tr>
<tr>
<td>18</td>
<td>wood</td>
<td>J</td>
<td>8.84E+14</td>
<td>5.86E+04</td>
<td>5.18E+19</td>
<td>1.58E+14</td>
<td>0.5901</td>
</tr>
<tr>
<td>19</td>
<td>fuelwood</td>
<td>J</td>
<td>1.73E+15</td>
<td>6.89E+04</td>
<td>1.01E+20</td>
<td>3.09E+14</td>
<td>0.9964</td>
</tr>
<tr>
<td></td>
<td>Water supply</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>6.84E+13</td>
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two consumption categories nearly equaled to the available local biocapacity.

The consumption of the gas regulation service, calculated in the conventional method as fossil fuel footprint, accounted for 13% of the total, which was different from that of the typical industrialized regions where the percentage of this kind of footprint represented between one and two thirds of the entire value of the ecological footprint (Bagliani et al. 2008). However, the percentages the consumption of waste treatment and erosion control services had occupied indicated that the traditional agricultural area was under threats from modernization and other technological and economic changes. Since the traditional rice-fish agricultural system is rapidly being substituted by the modern single planting system, the beneficial interactions promoted by the complex system between rice and fish have disappeared. Therefore, farmers have to put in a large amount of chemical fertilizers to increase the soil nutrient contents as well as pesticides and herbicides to control insects and weeds, which has caused severe non-point pollution and top soil loss in the traditional agricultural areas. The water supply category accounted in the EEF included water for industrial use, domestic use, irrigation and livestock. Although its footprint only registered 1% of the total amount, the incorporation of this category was another difference from the conventional method and it, together with others, could truly reflect the consumption of the local inhabitants.

5 Discussions

5.1 The quantitative comparison of results between EEF and EF

As is mentioned in Section 4.3, the local biocapacity could only meet 64% of the total consumption needed by the local inhabitants, leaving an ecological deficit of 5.2327 gha per capita. However, Congjiang County was characterized by a small ecological reserve through the conventional ecological footprint calculation, with the biocapacity and ecological footprint being 0.8748 and 0.8167 gha per capita respectively, which meant that the whole demand of natural resources by the local people could be achieved locally (Jiao et al. 2009).

Some may argue that the significant difference in the results is probably caused by the difference in the theories the two methods are based on. The conventional ecological footprint starts from matter flows and translates them into corresponding bioproductive lands using global yield while the EEF method begins with energy flows of a system and converts them into bioproductive areas through the method of emergy analysis. Here we adopted the load capacity factor introduced by Siche et al. (2007), which was obtained through the division of biocapacity values by footprint values (BC/EF), in order to make a better comparison between results calculated with the two different methods.

An examination of Table 4 indicated that the load capacity factor obtained with the EEF method for Congjiang County still showed a worse performance than that with the conventional method. The BC/EF ratio of the conventional method was 1.0689, which meant that in 2007 Congjiang County had the capacity to support 1.0689 times its population without causing damage to the environment, while the BC/EF ratio of the EEF method told us that the local biocapacity of Congjiang County could only meet 64% of the whole demand of ecosystem services by the local inhabitants and the 36% left might be met through imports or ruinous practices.

5.2 The methodological comparison between EEF and EF

Analyses with both the ecological balance and the load capacity factor have attained the same conclusion that the results obtained with the EEF method for Congjiang County showed a worse performance than those with the conventional method. However, we cannot conclude that the results through the EEF calculation are better than those through the calculation of the conventional method, because the EEF method has some deficiencies that have made limitations on its accuracy. One limitation of the EEF method is the scarcity of information on transformities for many resources and processes, which could make the results less accurate. Moreover, the biocapacity calculated using EEF method cannot be separated in the same categories used in the footprint calculation so it is impossible to make comparisons between the categories as is common in the conventional method.

But it is important to be noted that, in the present conversion to world average productivity, much information about impacts on regional ecosystems has been lost in the conventional method. In contrast, the enhanced EEF method includes a lot of elements that have important influences on regional sustainability, such as water supply, waste treatment and erosion control. Furthermore, the enhanced EEF method is capable of capturing almost all the ecological functions of all the land types because of its robust foundation on emergy analysis which analyses all kinds of resources, goods and services.
that humans consume. Thus, we believe that the enhanced EEF method is able to figure out the true ecological footprint of a region and reflect the influences humans have imposed on the environment in an all-round way. More individual characteristics (or differences) between the enhanced EEF method and the conventional method are expressed in Table 5.

### 6 Conclusions

Ecological footprint aims to measure human demand on the environment as accurately as possible, but it fails to do so since it does not fully capture the ecosystem services humans consume. Emergy analysis, on the other hand, is more robust than the ecological footprint for it includes accounting of other kinds of flows that influence sustainability such as wastes, soil loss and water use. The introduction of emergy analysis on the ecological footprint avoids the disputable assumptions presumed by the ecological footprint and provides a consistent physical value to assess the sustainability of a region. In this paper, the EEF accounting procedure had been further investigated by introducing the concept of ecosystem services into the EEF framework. Here, biocapacity was defined as the total quantity of available flows of services that the natural capital stocks provide in a given region while ecological footprint was defined as the amount of flows of ecosystem services required to support the consumption of a given population. The EEF-based sustainability assessment could be regarded as testing whether human consumption of ecosystem services jeopardizes the intactness of the natural capital they are derived from.

The enhanced EEF method was then applied to evaluate the sustainability of Congjiang County in Guizhou Province, a typically traditional agricultural area in China. Results showed that the local biocapacity could only meet 64% of the total consumption needed by the local inhabitants, leaving an ecological deficit of 5.2327 gha per capita, as opposed to the results obtained through the conventional method that Congjiang County was characterized by a small ecological reserve. This paper also adopted the load capacity factor (BC/EF) for better comparison of results calculated with the two different methods. And the same conclusion was drawn that results obtained with the EEF method for Congjiang County showed a worse performance, which meant Congjiang County was unable to support its population with its present way of managing the ecosystem. The disaggregated analysis showed that the consumption of waste treatment and erosion control services occupied a considerable proportion of the ecological footprint, which implied that the traditional agricultural areas were under severe threat from modernization and other technological and economic changes. The results of the study recommend that, if possible, the local population of Congjiang County avoid large-scale substitution of traditional rice-fish systems and limit the use of chemical fertilizers and pesticides for its reasonable conservation and sustainable development.

Although it has some deficiencies in transformity information and category comparison which have made limitations on its accuracy, the enhanced EEF method is capable of capturing almost all the ecological functions of land and including a lot of elements that have important influences on regional sustainability because of its robust foundation on emergy analysis. Thus, we believe that the enhanced EEF method is able to figure out the true ecological footprint of a region and reflect the influences humans have imposed on the environment in an all-round way. The results of this study further certified our belief that utilizing the emergy analysis to include all the flows of ecosystem services the local inhabitants consumed in the ecological footprint could enable EEF a better indicator of the regional sustainability.

### References


传统农业地区能值生态足迹分析——以贵州省从江县为例

摘要: 传统农业生态系统正面临着来自现代化发展及其带来的技术经济变革的严重威胁。在一些传统农业地区现代农业及次系统的影响下, 传统农业已经引发了严重的生态环境问题。生态足迹, 作为可持续发展评价的方法之一, 由于无法全面衡量人类活动对生态系统造成的影响, 因此无法揭示传统农业地区真实的生态环境状况。没有给出科学合理的可持续发展评价。能值生态足迹是对传统生态足迹的一种改进, 试图利用能值分析理论的优点囊括人类利用生态系统产品和服务的各种活动。然而, 目前能值生态足迹研究往往受到传统生态足迹理论的局限, 无法真正将人类消费的各种资源、产品和服务纳入进来。本文将生态足迹服务概念引入能值生态足迹模型中, 进一步改进和完善了能值生态足迹模型, 使之能够全面衡量人类活动的生态环境影响。本文利用改进的能值生态足迹模型, 以我国传统农业地区贵州省从江县为例, 开展生态环境状况评估和可持续发展评价。结果表明, 从江县2007年人均能值生态足迹为9.3311 ha, 人均能值生态足迹为14.5638 ha, 人均能值生态赤字为5.2327 ha。可见, 从江县的生态承载力仅能满足当地居民消费需求的64%, 当地处于不可持续发展状态, 生态环境状况不容乐观。这与传统生态足迹的评价结果差异十分显著。传统生态足迹评价结果显示, 从江县的生态承载力不仅能够满足当地居民的消费需求而且有少量生态盈余。进一步分析显示, 从江县居民对生态系统的污染物吸纳服务和侵蚀控制服务的消费, 在从江县总生态足迹中占有相当大的比例。这说明, 从江县传统农业生产方式受现代农业影响而发生的部分改变, 所产生的生态环境影响已经逐步显现。过量施用化肥农药所引起的面源污染以及频繁翻耕和砍伐森林所引起的水土流失, 已经严重威胁当地的生态环境健康和可持续发展。

关键词: 能值生态足迹; 生态足迹; 能值; 生态系统服务; 可持续发展评价; 传统农业地区
Appendix A: Notes to Table 2

1. Sun, solar energy
   Area = 3.24E+09 m²
   Insolation = 3.88E+09 J m⁻² y⁻¹
   Albedo = 0.25
   Energy = (area) × (insolation) × (1-albedo) × (1/0.25) × (9.43E+18 J y⁻¹)

2. Rain, geopotential energy
   Area = 3.24E+09 m²
   Evapotranspiration = 1.19E+00 m y⁻¹
   Density of water = 1.00E+03 kg m⁻³
   Energy = (area) × (evapotranspiration) × (density of water) × (1.90E+16 J y⁻¹)

3. Rain, geopotential energy
   Area = 3.24E+09 m²
   Runoff = 0.70E+00 m y⁻¹
   Density of air = 1.30E+00 kg m⁻³
   Energy = (area) × (runoff) × (density of air) × (9.43E+18 J y⁻¹)

4. Wind, kinetic energy
   Wind velocity = 1.15 m s⁻¹
   Energy = (quantity) × (energy content)

5. Geothermal energy
   Energy = (area) × (heat flow)

Appendix B: Notes to Table 3

1. Food production
   (1) Rice
       Quantity = 7.74E+10 g y⁻¹
       Energy content = 1.55E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (2) Wheat
       Quantity = 3.62E+09 g y⁻¹
       Energy content = 1.38E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (3) Sweet potatoes
       Quantity = 6.11E+09 g y⁻¹
       Energy content = 1.38E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (4) Corn
       Quantity = 8.58E+09 g y⁻¹
       Energy content = 1.97E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (5) Potatoes
       Quantity = 7.95E+09 g y⁻¹
       Energy content = 1.57E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (6) Peanuts
       Quantity = 1.44E+09 g y⁻¹
       Energy content = 3.22E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (7) Beans
       Quantity = 1.99E+09 g y⁻¹
       Energy content = 2.44E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (8) Vegetables
       Quantity = 7.39E+10 g y⁻¹
       Energy content = 4.19E+03 J g⁻¹
       Energy = (quantity) × (energy content)

   (9) Watermelons
       Quantity = 1.55E+10 g y⁻¹
       Energy content = 1.75E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (10) Oranges
        Quantity = 3.15E+10 g y⁻¹
        Energy content = 1.76E+04 J g⁻¹
        Energy = (quantity) × (energy content)

   (11) Beef
        Quantity = 2.43E+09 g y⁻¹
        Energy content = 5.64E+04 J g⁻¹
        Energy = (quantity) × (energy content)

2. Raw materials
   (1) Rapseeds
       Quantity = 7.39E+09 g y⁻¹
       Energy content = 1.85E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (2) Cotton
       Quantity = 5.0E+07 g y⁻¹
       Energy content = 1.70E+04 J g⁻¹
       Energy = (quantity) × (energy content)

   (3) Sugar cane
       Quantity = 7.95E+09 g y⁻¹
       Energy content = 8.50E+11 J y⁻¹

3. Water supply
   (1) Water for industrial use
       Volume = 9.0E+06 m³ y⁻¹
       Energy content = 4.96E+06 J m⁻³
       Energy = (volume) × (energy content)

   (2) Water for domestic use
       Volume = 1.38E+07 m³ y⁻¹
       Energy content = 4.96E+06 J m⁻³
       Energy = (volume) × (energy content)

   (3) Water for irrigation and livestock
       Volume = 9.24E+07 m³ y⁻¹
       Energy content = 4.96E+06 J m⁻³
       Energy = (volume) × (energy content)

4. Gas regulation
   (1) Electricity
       Volume = 1.50E+08 kWh y⁻¹
       Energy content = 3.6E+06 J kWh⁻¹
       Energy = (volume) × (energy content)

   (2) Coal
       Quantity = 1.21E+07 kg y⁻¹
       Energy content = 2.68E+07 J kg⁻¹
       Energy = (quantity) × (energy content)

   (3) Fuel (includes diesel, gasoline and lubricants)
       Quantity = 3.49E+07 L y⁻¹
       Energy content = 4.78E+07 J L⁻¹
       Energy = (quantity) × (energy content)

5. Waste treatment
   (1) Nitrogen fertilizers
       N content = 1.48E+09 g y⁻¹
       Energy = (quantity) × (energy content)

   (2) Phosphate fertilizers
       P₂O₅ content = 5.21E+08 g y⁻¹
       Energy = (quantity) × (energy content)

   (3) Potash fertilizers
       K₂O content = 7.64E+08 g y⁻¹
       Energy = (quantity) × (energy content)

   (4) Compound fertilizers
       Quantity = 3.64E+09 g y⁻¹
       Energy = (quantity) × (energy content)

   (5) Pesticides
       Quantity = 2.32E+08 g y⁻¹
       Energy = (quantity) × (energy content)

6. Erosion control
   Area of soil erosion = 5.59E+08 m²
   Average rate of soil erosion = 2.00E–03 m y⁻¹
   Density of soil = 1.05E+06 g m⁻³
   Average organic content = 3.58E–02
   Energy content of organic matter = 2.25E+04 J g⁻¹
   Energy = (area of soil erosion) × (average rate of soil erosion) × (density of soil) × (average organic content) × (energy content of organic matter)