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A modified method of ecological footprint calculation and its application

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Abstract

As economic and ecological support systems become more interdependent, new disciplines are needed to "bridge the gap" between human and nature. "Emergy" created by H.T. Odum is a new method for evaluating natural capital and ecosystem services. The "ecological footprint" created by Wackernagel and Rees has been promoted as a policy and planning tool for sustainability. The aim of this paper is to show a modified form of ecological footprint calculation by combining emergy analysis with conventional ecological footprint form of calculations. Our new method starts from the energy flows of a system in calculating ecological footprint and carrying capacity. Through a study of the energy flows, and using the method of emergy analysis, the energy flows of a system are translated into corresponding biological productive units. To demonstrate the mechanics of this new method, we compared our calculations with that of an original calculation of ecological footprint of a regional case. We select Gansu province in western China, as an example for application of our study. In this case the same conclusions were drawn using both methods: that Gansu province runs an ecological deficit.

Keywords: Ecological footprint; Carrying capacity; Emergy

1. Introduction

The human economy depends on the planet's natural capital that provides all ecological services and natural resources. Humans have had a considerable impact on the earth, associated with population increase and economic development. We face a series of contradictions among the natural resources, environment, and economy, such as population growth, resources depression and environment deterioration. The implication of this ecological maxim is obvious: to be sustainable, humanity must live within nature's carrying capacity. Since the early 1970s, one report after another have warned that unlimited growth of human population and consumption is not sustainable. Among the most prominent of these reports are "The Limits to Growth" (Meadows et al., 1972), Brundtland Commission's "Our Common Future" (WCED, 1987), and Worldwatch Institute's annual "State of the World" publications. We seem to be

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getting further and further away from sustainability. To make sustainability a reality, we must measure where we are now and how much further we can go. Indicators of progress are needed. In the new methods of valuation, measurement of sustainability has gone from qualitative analysis to quantitative analysis. In recent years, there has been some positive development with new valuation tools making substantial headway, in particular Wackernagel and Rees's (1996) method known as ecological footprint, and Odum's (1996) method of emergy accounting. The methods of these approaches are different, but they aim to solve the same problems through accounting in some way or another humanity's energy and resources throughput, estimating the gap between demand of humanity and natural services, and appraising the situation of natural resource utilization.

The aim of this paper is to show a modified ecological footprint calculation. The paper will be structured in four parts:

1. introduction to emergy accounting;
2. introduction to ecological footprint calculation;
3. a modified method of ecological footprint calculation;
4. case study of a region and discussion.

2. Concept of emergy accounting

2.1. Basic definition

Emergy analysis has been developed over the past 20 years by Odum (1988, 1996). Emergy measures both the work of nature and that of humans in generating products and services, as a science-based evaluation system that represents both natural values and economic values with a simple, universal unit. Emergy analysis is based on the principle of energetic (Lotka, 1922), systems theory (Von, 1968), and system ecology (Odum, 1983). Emergy provides a tool for different kinds of energy flows and materials in a system. Some emergy analyses gave detailed descriptions of emergy analysis (Federici et al., 2003; Brown and McClanahan, 1996; Ulgiati et al., 1995). A fuller treatment of the theoretical background to the emergy approach can be found in Odum (1988, 1998); Odum et al. (2000); Brown and Ulgiati (2001). Brown and Ulgiati (2004) trace development of the theory and concepts of emergy and Hau and Bakshi (2004) review the concept of emergy together with a discussion of both its conceptual strengths and criticisms by others.

Emergy (spelled with an 'm') is defined as the energy of one type required in transformations to generate a flow and storage (Odum, 1988). In this account solar emergy is used. Solar emergy of a flow or storage is the solar energy required to generate that flow or storage. Its units are solar emergy emjoules (abbreviation: sej). It evaluates the work previously used up directly and indirectly to make a product or services. The transformity is defined as the amount of emergy of one type required directly and indirectly to generate a unit of energy of another type (Odum, 1988). It is the emergy per unit energy in units of emjoules per Joule which constitutes the ratio of emergy to available energy. The units of transformity are solar emjoules/Joule, abbreviated sej/J or solar emjoules/g (sej/g). The higher the transformity, the higher that item is located in the energy hierarchy chain, This is based on the assumption implicit in the maximum power principle that the more energy required to make a product or service, the higher its emergy value. As its name implies, the transformity can be used to transform a given energy into emergy, by multiplying the energy by its transformity. Once transformities are known for a class of item, the total emergy of an item can be expressed as:

$$\text{emergy} = \text{available energy of item} \times \text{transformity}$$

2.2. The emergy analysis method

The general methods for employing emergy synthesis are described by Odum (1996) and Odum et al. (2000). The analysis is conducted using an emergy analysis table (Table 1). Table 1 demonstrates how items are transformed from raw units to solar emergy.

2.3. Emergy indices

Once the total number of input flows has been identified and the total emergy driving a process has been evaluated, a set of indices can be calculated. In Fig. 1 and Table 2, several of these indices are defined. Some researchers have defined such indices and ratios to illuminate different aspects of sustainability (Ulgiati et al., 1995; Odum, 1996; Brown and Ulgiati, 1997; Ulgiati

Table 1
Template for inventorying and weighting resource inputs and outputs in emergy synthesis

1 Note	2 Item	3 Data	4 Transformity	5 Solar emergy

Column 1 is the line item number and footnote number that contains sources and calculations for the item. Column 2 is the name of the item. Column 3 is the raw data in Joules, grams, dollars or other units, usually evaluated as flux per year. Column 4 is the transformity used for calculations, expressed in solar emergy Joules per Joule or other appropriate units (sej/h; sej/g; sej/$). Transformities may be obtained from previous studies. Column 5 is the solar emergy of a given flow, calculated as input times transformity (Column 3 × Column 4).

and Brown, 1998; Bastianoni et al., 2001; Brown and Buranakarn, 2003; Yang et al., 2003).

3. The ecological footprint

Ecological footprint has been developed by Wackernagel and Rees (1996); Wackernagel et al. (1999). The ecological footprint of any defined population (from a single individual to a whole city or country) is the area of biotically productive land and water appropriated exclusively to produce the resource used and to assimilate the waste generated by the population. Ecological footprint calculations are based on two simple assumptions: first, that we can keep track of most of the resource we use and many of the waste

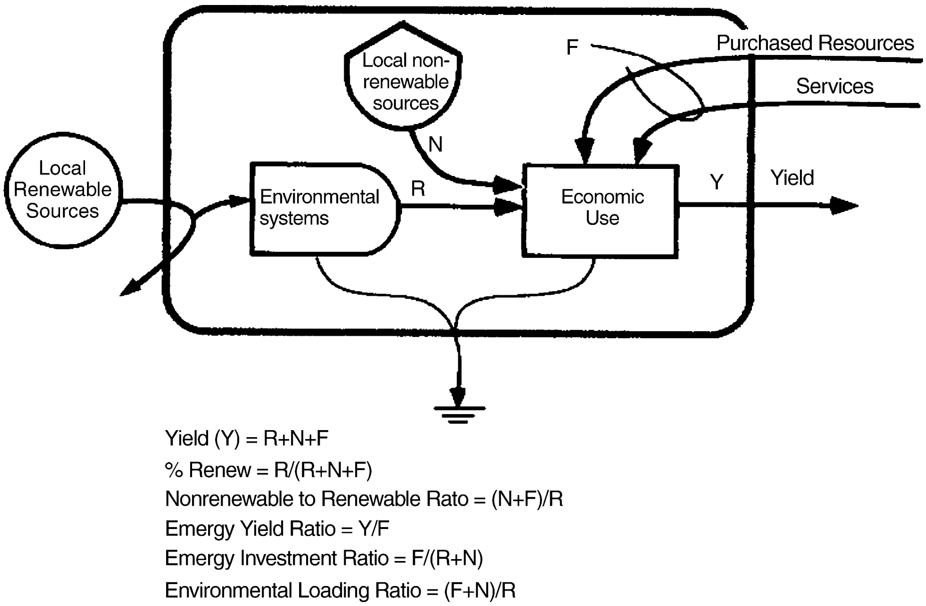

Fig. 1. Emergy based indices, accounting for local renewable emergy inputs (R), local nonrenewable inputs (N), and purchased inputs from outside the system (F). (Brown and Ulgiati, 1997).

Table 2
Emergy-based indices

Indices	Expression	Signification
Emergy investment ratio (EIR)	$F/(N+R)$	The ratio of emergy F fed back from outside the system to the indigenous emergy inputs ($N+R$)
Emergy yield ratio (EYR)	Y/F	The ratio of the emergy of the output Y divided by the emergy of those inputs F to the process that are fed back from outside the system under study
Environmental loading ratio (ELR)	$(F+N/R)$	The ratio of purchased F and nonrenewable indigenous emergy N to free environmental emergy R
Index of sustainability (ESI)	EYR/ELR	The emergy yield ratio divided by environmental loading ratio

we generate; secondly, that most of these resource and waste flows can be converted to a corresponding biotically productive area (Wackernagel et al., 1999). As the ecological footprint and carrying capacity are both measured in the same units, they can be compared directly. If the ecological footprint of a region is larger than the carrying capacity, the region runs an ecological deficit. If the carrying capacity of a region is larger than ecological footprint, the region runs an ecological remainder.

In the analysis of ecological footprint, six main categories of ecologically productive area are distinguished: crop land, pasture, forest, water area, built-up and energy land. As the various ecological categories represent large differences in biological productivity, Wackernagel et al. (1999) uses 'biological productive areas with world average productivity' as a common measurement unit for footprints and carrying capacity. Using world average yield, consumption and waste absorption are translated into appropriated biologically productive areas. To aggregate the biologically productive areas in a more accurate and realistic way, they are multiplied with 'equivalence factor'. In the calculation of carrying capacity, 'yield factors' are introduced. Some countries or regions are better endowed with ecological productivity by having either more space available and/or ecosystems and agroecosysytems of higher productivity per unit area. Therefore, to document the ecological production available within a country or region, the number of physical hectares of biotically productive area that exist in each ecological category within the country or the region is multiplied by the factor by which the country's or region's ecosystem differ in productivity from the world average. This factor is the 'yield factor'. After the concept of ecological footprint was developed, some analyses include detailed descriptions of the ecological footprint method (Wackernagel et al., 1999, 2002; Haberl et al., 2001; van Vuuren and Smeets, 2000; Senbel et al., 2003).

4. A modified method of ecological footprint calculation

Influence of the emergy analysis on the academic circles of ecology and economic is great. Emergy analysis considers all systems to be networks of energy flow and determines the emergy value of the streams and systems involved. It is a quantitative measure of the resources required to develop a product, whether it is a mineral resource, a biological resource or a commercial product; and it expresses the resources in units of one type of energy, usually, solar emergy. It provides a bridge between ecological and economic systems. It is a new method for quantitative analysis of ecosystems, even complex ecosystems. It provides common units for analyzing all kinds of flows in an ecosystem. As a helpful tool for evaluating rational use of natural resources, it provides a system for quantifying facts for evaluating environment resources. The ecological footprint, on the other hand, offers a cheap and rapid natural capital appraisal method for nations to compare human demands with nature's available supply for human use. The footprint is an accounting tool that can aggregate ecological consumption in an ecologically meaningful way. The ecological footprint is promoted as a policy and planning tool for sustainability (Wackernagel and Silverstein, 2000). It can offer a measure of carrying capacity available for human use, become an indicator of sustainability and provide a target for assessing progress (Wackernagel and Yount, 1998).

Some researchers claim that emergy assessments can be converted into numerical values of space equivalents, providing another venue for calculating ecological footprints (Wackernagel and Yount, 2000). In this paper we present a new method of ecological footprint calculation, based on the emergy analysis. The translation of human demand of natural resources and the supply of natural services into understandable and quantifiable concepts is the main objective of this new method. First, amounts of human consumption corresponding to six categories of ecological productive areas and amounts of natural supply are calculated. And then, these amounts are translated into common unit emergy through the emergy analysis. Finally, in this new method we are proposing, we will derive the ecological footprint and carrying capacity by dividing the emergy amounts by the emergy density. The detail calculation and analysis of this new method is express as follows.

4.1. Calculation of carrying capacity

The ecological footprint has its roots in the concept of the carrying capacity. As defined by biologists, carrying capacity is the number of individuals of a given species that a given habitat can support without being permanently damaged (Odum, 1989; Rees, 1992). If the population of a given species exceeds the carrying capacity of a given habitat, then either the resources required to meet the needs of that species will be depleted, or the wastes produced by that species will build to the point of poisoning members of the species, or both, and the population will crash. An environment's carrying capacity is its maximum persistently supportable load (Carton, 1986). Humankind remains in a state of "obligate dependence" on the productivity and life support services of the ecosphere (Rees, 1990). Therefore, the carrying capacity remains central to sustainability. For sustainability, a critical minimal amount of such capital must be conserved intact and in place. In this light, the fundamental question for ecological sustainability is whether remaining natural capital stocks (including other species populations and ecosystems) are adequate to provide the resources consumed and assimilate the wastes produced by the anticipated human population into the next century, while simultaneously maintaining the general life support functions of the ecosphere (Rees, 1996). The issue becomes clearer if we define human carrying capacity not as a maximum population but rather as the maximum (entropic) "load" that can safely be imposed on the environment by people (Carton, 1986). A better understanding of carrying capacity can be gained by separating the natural resources for society into renewable and nonrenewable components. The distinction between renewable and nonrenewable resources is somewhat artificial because all resources on earth are renewed by the global web of ecological processes; however, those that are being renewed very slowly compared to their rate of use are said to be nonrenewable. The nonrenewable resources are depleted because they are being used at a rate that exceeds their rate of replacement. Carrying capacity is not sustainable unless it is based on the use of resources in a renewable way. So, the only renewable resources would be taken into account in our calculation of carrying capacity. By inverting the standard carrying capacity ratio and extending the concept of load, we can use ecological footprint for assessing human carrying capacity. Ecological footprints are denominated in hectares per capita, whereas carrying capacity is generally expressed in units of individuals per hectare, making one concept the inverse of the other.

The following equation is used to estimate the carrying capacity:

$$\mathrm{cc} = \frac{e}{p_1} \tag{1}$$

where cc is the carrying capacity per capita (ha); e is the renewable resources of emergy amount per capita (sej); p_1 is the earth emergy density, it is the emergy amount per unit time of the earth (sej/m^2·a); the following equation is used to calculate it:

$$p_1 = \frac{\text{total emergy of the earth}}{\text{areas of the earth}} = \frac{1.583\times10^{25}\text{sej}}{5.1\times10^{14}\text{m}^2} = 3.1\times10^{10}\text{sej/m}^2\cdot\text{a}$$

The total emergy amount 1.583×10^{25} sej of the earth in one year is taken from Odum et al. (2000; also see Table 3). The total emergy amount of the earth is the sum of the emergy of solar insolation, deep earth heat and tidal energy.

4.2. Calculation of ecological footprint

The calculation procedure proposed by Wackernagel and his colleagues involves using consumption and population statistics to calculate the 'average person's' annual consumption for several items in each of the consumption categories. The area appropriated by each person can then be calculated by dividing the annual per capita consumption by the average annual productivity or yield for each item consumed. The total per capita ecological footprint is obtained by summing all ecosystem areas appropriated for each item consumed during a particular time period.

The basic calculations for ecological footprint estimates are conceptually simple. First we estimate the annual per capita consumption of major consumption items from aggregate regional or national data by dividing total consumption by population size. Much of the data needed for preliminary assessments is readily available from national statistical tables on, for example, energy, food, or forest products production and consumption. For many categories, national statistics provide both production and trade figures from which consumption can be assessed:

$$\text{consumption} = \text{production} + \text{imports} - \text{exports}$$

The next step is to estimate the land area appropriated per capita for the production of each consumption item

Table 3
Total emergy amount of the earth

Energy item	Energy (J/a)	Solar transformity (sej/J)	Solar emergy (sej/a)
Solar insolation	3.93E+24	1	3.93E+24
Deep earth heat	6.72E+20	1.2E+4	8.06E+24
Tidal energy	0.52E+20	7.39E+4	3.84E+24
Total			1.583E+25

by dividing average annual consumption of that item by its average annual productivity or yield. For example, in the case of potatoes, the footprint component would be:

$$\frac{\text{production}_{\text{potatoes}} + \text{import}_{\text{potatoes}} - \text{export}_{\text{potatoes}}}{\text{yield}_{\text{potatoes}}} = \text{footprint\_component}_{\text{potatoes}}$$

We then compile the total average per capita ecological footprint (ef) by summing all the ecosystem areas appropriated for each item consumed. Finally we obtain the ecological footprint (EF) of the study population by multiplying the average per capita footprint by population size (N): thus, $\text{EF} = N \times \text{ef}$.

According to the original calculation model for fossil energy can be calculated in three ways (Stöglehner, 2003):

1. In the first calculation method the footprint of fossil fuels is expressed by the land need of an energy carrier produced by agriculture or forestry, i.e. the area that is necessary for the production of the same amount of energy as generated by fossil fuels. The substitute products for the fossil energies are ethanol from agricultural production or methanol from forest production. Prior studies, reported in Wackernagel and Rees (1996), suggest an energy productivity of 80–150 GJ/ha per year for these fuels.
2. The second calculation method suggests calculating the land need for fossil energy consumption by assessing the forest area that is necessary to absorb the carbon dioxide emissions generated by burning fossil fuels.
3. In the third calculation method the land need for fossil energy is estimated by the area needed to compensate the amount of energy burned from fossil fuels with renewable resources at the same rate at which the fossil energy is depleted.

According to the original calculation model of Wackernagel and Rees the modified calculation model for the ecological footprint is estimated by the following equation:

$$\text{ef} = \sum_{i=1}^{n} a_i = \sum_{i=1}^{n} \frac{c_i}{p_2} \tag{2}$$

In the Eq. (2), ef is the ecological footprint per capita (ha); i are the kinds of natural resources; a_i is the corresponding areas of no. i resources per capita (ha); c_i is the emergy amount of no. i resource per capita (sej); p_2 (sej/m^2 a) is a region emergy density, it is the emergy amount per unit time of a region; the following equation is used to calculate the p_2:

$$p_2 = \frac{\text{total emergy of a region}}{\text{areas of a region}}$$

In calculation of the total emergy of a region, five kinds of renewable resources emergy are considered: sun, wind, chemical energy in rain, geopotential energy in rain, and earth cycle energy. The maximum item of emergy amount is regarded as the total emergy of a region.

For example, in the case of cereal, the footprint component would be:

$$\text{ef}_{\text{cereal}}(\text{m}^2) = \frac{C_{\text{cereal}}}{p_2} = \frac{[\text{consumption}_{\text{cereal}}(J) \times \text{transformity}_{\text{cereal}}(\text{sej/J})]/N}{p_2(\text{sej/m}^2)},$$

here C_{cereal} is the emergy amounts of cereal consumption per capita; N is the population size of a region.

The calculation of this new method consists of two components. One is the carrying capacity; the other is the ecological footprint. In the calculation of the carrying capacity, first, the emergy amounts of available renewable resources are estimated. Here, five kinds of renewable resources emergy are considered: sun, wind, chemical energy in rain, geopotential energy in rain, and earth cycle energy. In order to avoid duplicate calculation, the maximum item of emergy amount is regarded as the total available emergy. Thus, this amount is divided by the amount of population. We get the amount of e in Eq. (1) the emergy supply of natural resources per capita. And then, the amount of e is divided by the emergy density p_1. We get the carrying capacity per capita (cc). In the calculation of ecological footprint, it is composed by two parts: (1) biological resources, (2) energy resources. In the footprint accounting of biological resources, four kinds of the consumption emergy are distinguished: agriculture, forestry, animal husbandry, and fishery. In the calculation of energy resources, four kinds of commercial energies are considered: coal, natural gas, liquid fossil fuel, and electricity. The actual consumption amounts of these two kinds of natural resources (biological resources and energy resources) are calculated respectively, and these amounts are translated into the common units emergy. These emergy amounts are divided by the population to get the c_i in Eq. (2). The amount of c_i is divided by the region emergy density p_2 to get the footprint, and all the footprints are added together to get the ef of ecological footprint per capita.

5. A case study

To demonstrate the mechanics of this new method and compare it with the original calculation of ecological footprint, a regional case is presented here. We select the Gansu province in western China as an example. The boundary of the region of this study is an administrative division. We argue that it is useful to analyse ecological footprints at the regional level and compare the results with other regions because administrative divisions are based on the largest decision-making body in a nation. Table 4 presents the full process of modified calculation of ecological footprints and carrying capacity in the Gansu province in the year 2000. Tables 5 and 6 are the final results of the modified and the original calculations, respectively, for the ecological footprints and carrying capacity in the Gansu province in the year 2000.

Table 4 is composed of two main sections. The upper part consists of the supply of renewable resources. The rows represent resources types. The columns specify the original data, transformity, total emergy, emergy per capita, and carrying capacity per capita. In Table 4, we get e as 1.19×10^{15} sej/cap in Eq. (1). According to Eq. (1), the carrying capacity (cc) of Gansu province was 3.8326 ha. In the bottom part, the consumption is summarized. Here, all of the footprint components are added to obtain the total footprint. It is composed of five areas of consumption: agriculture, forestry, animal husbandry, fishery, and energy resources. Based on the equation for calculating p_2 and Eq. (2), we get 6.586×10^{10} sej/m^2 as the regional emergy density (p_2) of Gansu province. The ecological footprint of Gansu province in the year 2000 was 5.1538 ha/cap. In Table 5, the final results are summarized in two boxes. The left box itemizes the ecological footprint in two categories, biological resources, energy resources, as well as the total. The results are presented as per capita figures. The right box shows how much biotical productive capacity exists within Gansu province. As proposed by WCED (1987), at least 12% of the earth's carrying capacity is available for biodiversity protection. Although 12% may not be enough for securing biodiversity in the long term (Noss and Cooperrider, 1994), conserving more at this time may not be politically feasible. So the final carrying capacity is reduced by 12% for biodiversity protection. With 12% set aside for biodiversity protection, the carrying capacity of Gansu province dropped from 3.8326 ha/cap down to 3.3727 ha/cap. We can draw this conclusion: the ecological footprint of the region is larger than the carrying capacity. Consequently, the regional ecological deficit was 1.7811 ha/cap.

We also used the conventional method of Wackernagel et al. (1999) to calculate the ecological footprints and the carrying capacity in Gansu province in the year 2000. The results are shown in Table 6. The ecological footprint was 1.7456 ha and the carrying capacity was 1.6686 ha. We can draw the same conclusion: the region runs an ecological deficit.

6. Discussion

The ecological footprint provides a measure of demands upon the biological productivity and assimilative capacity of nature imposed by human lifestyles. Early descriptions and development of ecological foot-

Table 4
Calculations for ecological footprint and carrying capacity in the Gansu province (2000)

Item	Raw date (J)	Transformity[a] (sej/J)	Total emergy (sej)	Emergy per capita (sej)	Carrying capacity per capita (ha/cap)
Population: 25121200; areas: 4.54E+11 m^2; p_1 = 3.104E+10					
Carrying capacity			2.99E+22	1.19E+15	3.8326
Renewable resources			2.99E+22	1.19E+15	3.8326
Sun	1.78E+21	1	1.78E+21	7.10E+13	0.2288
Rain chemical	6.78E+17	15444	1.05E+22	4.17E+14	1.3428
Rain geo-potential	3.36E+18	8888	2.99E+22	1.19E+15	3.8326
Wind	1.43E+17	663	9.48E+19	3.77E+12	0.0122
Earth cycle	9.09E+17	29000	2.64E+22	1.05E+15	3.3802

Item	Raw date (J)	Transformity[a] (sej/J)	Total emergy (sej)	Emergy per capita (sej)	Carrying capacity per capita (ha/cap)
Population: 25121200; areas: 4.54E+11 m^2; p_2 = 6.586E+10					
Ecological footprint			8.53E+22	3.39E+15	5.1538
Biological resources			3.58E+22	1.43E+15	2.166
Farm crops			2.17E+22	8.64E+14	1.3126 Arable land
Cereal	7.17E+16	35900	2.57E+21	1.02E+14	0.1555 Arable land
Wheat	3.68E+16	68000	2.50E+21	9.95E+13	0.1511 Arable land
Corn	3.08E+16	58100	1.79E+21	7.13E+13	0.1083 Arable land
Beans	6.94E+15	690000	4.79E+21	1.91E+14	0.2895 Arable land
Tubers	2.42E+15	2700	6.53E+18	2.60E+11	0.0004 Arable land
Oil-bearing crops	1.06E+16	690000	7.34E+21	2.92E+14	0.4437 Arable land
Cotton	1.08E+15	1900000	2.06E+21	8.19E+13	0.1244 Arable land
Vegetables	2.10E+16	27000	5.67E+20	2.26E+13	0.0342 Arable land
Beetroots	1.06E+15	84900	9.02E+19	3.59E+12	0.0055 Arable land
Forestry			1.51E+21	6.02E+13	0.0914 Forest
Fruits	2.80E+15	530000	1.48E+21	5.91E+13	0.0897 Forest
Wood	8.11E+14	34900	2.83E+19	1.13E+12	0.0017 Forest
Animal husbandry			1.25E+22	4.97E+14	0.7548 Pasture
Meats	2.80E+15	3170000	8.89E+21	3.54E+14	0.5374 Pasture
Milks	6.33E+14	1700000	1.08E+21	4.28E+13	0.0650 Pasture
Eggs	5.14E+14	2000000	1.03E+21	4.09E+13	0.0622 Pasture
Wool	3.39E+14	4400000	1.49E+21	5.94E+13	0.0902 Pasture
Fishery	6.49E+13	2000000	1.30E+20	5.16E+12	0.0078 Water area
Energy resources			4.94E+22	1.97E+15	2.9872
Coal	5.08E+17	39800	2.02E+22	8.05E+14	1.2224 Fossil land
Petroleum	3.69E+17	53000	1.95E+22	7.78E+14	1.1812 Fossil land
Natural gas	3.31E+15	48000	1.59E+20	6.32E+12	0.0096 Fossil land
Electric	5.97E+16	1.59E+05	9.50E+21	3.78E+14	0.5740 Built-up area

[a] The transformities are taken or modified from Odum (1996).

print analysis (Rees, 1992; Wackernagel and Rees, 1996) have been followed by debate on various aspects of the utility of the technique (Levett, 1998; Wackernagel, 1998a,b; van den Bergh and Verbruggen, 1999; Ferguson, 1999). Despite this ongoing debate, and some recognized limitations inherent in the technique, it is clear that ecological footprint calculations are becoming more frequent employed and better understood (Hunter, 2002). The ecological footprint calculation framework has become a starting point for many national and regional accounting of ecological flows and services. This biogeophysical interpretation used by the ecological footprint concept has some advantages. First it makes the results more accessible.

Table 5
Ecological footprints summary in the Gansu Province (2000)

Ecological footprint		Carrying capacity	
Category	Total (ha/cap)	Category	Total (ha/cap)
Fossil energy	2.4132	Renewable resources	3.8326
Built-up area	0.5740		
Arable land	1.3126		
Pasture	0.7548	12% for biodiversity	0.4599
Forest	0.0914		
Water	0.0078		
Total	5.1538	Total	3.3727

Second, and more importantly, the human "consumption" for ecological space can be compared easily to the earth's finite "supply" of space (Wackernagel and Yount, 1998). Third, like other aggregate indicators, it reduces and simplifies complex resource by reducing patterns to single numbers (Costanza, 2000). As such accounts can be summarized in single numbers, they may prove to be useful counterparts to the conventional gross domestic product (GDP) measure (Wackernagel et al., 1999). The direct and indirect land use based on emergy is similar to the concept of ecological footprint in that it relates resource use to an area. In this paper, based on the emergy analysis, we present a new method for calculation of the ecological footprint. It translates the production and consumption of different type resources into a common unit area. It offers a true measure of the carrying capacity of the ecological footprint. It gives us a clear outline of human impact on earth and human consumption of natural capital. As a new method for measuring the use of natural resources, it shows more clearly as to where we are and where we need to be.

The main difference between the new method and the conventional ecological footprint are expressed as follows: our new method starts from the energy flows of a system through calculations of ecological footprint and carrying capacity. Through the study on the energy flows, and using the method of emergy analysis, these energy flows are translated into corresponding biological productive areas. The form of calculation in this new method is based on the theory of emergy analysis. Using the concept of emergy density (p) that we present here, the supply of natural resources and consumption of humanity can be translated into an easily understandable concept. In contrast, when calculating conventional ecological footprint, one starts from mat-

Table 6
Conventional ecological footprints summary in the Gansu Province (2000)

Ecological footprint (per capita)				Carrying capacity (per capita)			
Category	Total	Equivalence factor	Equivalent total (ha/cap)	Category	Yield factor	Regional area (ha/cap)	Yield adjusted equiv. area (ha/cap)
Fossil energy	0.6906	1.1	0.7597				
Built-up area	0.0040	2.8	0.0112	Built-up area	1.49	0.0400	0.0596
Arable land	0.1865	2.8	0.5222	Arable land	1.49	0.1388	0.2068
Pasture	0.3927	1.1	0.4319	Pasture	2.19	0.6624	1.4506
Forest	0.0151	1.1	0.0166	Forest	0.8	0.1695	0.1356
Water	0.0193	0.2	0.0039	Water	1	0.0436	0.0436
				Total existing			1.8962
Total used			1.7456	Total available	(−12% for biodiversity)		1.6686

ter flows, or value flows, especially in calculations of biological resources such as arable land, forest and pasture. These matter flows are translated into corresponding biological productive areas. We derive the final amount of ecological footprint and carrying capacity by introducing the equivalence factor and yield factor in calculations of the conventional ecological footprint. The equivalence factor shows how much more productive a particular ecosystem category is as compared to average bioproductive space. The yield factor compares the productivity of an ecosystem category in a nation or a region to the world-average productivity of the same ecosystem category.

In most EF calculations published thus far, material flows are converted to area (hectares) using global yields of the respective year. However, in the present conversion to world-average productivity, much information about impacts on regional ecosystems has been lost. Haberl et al. (2001) analyze the effect different assumptions on yields have on the results of EF calculations by assuming: (1) constant global yields as of 1995; (2) variable global yields; and (3) variable local yields for domestic extraction and variable global yields for imported biomass. These three methods led to dramatically different results. Furthermore, an evaluation of energy supplies is not possible through either of the three calculation methods of the original calculation model for the energy footprint mentioned earlier because these calculation methods do not determine the area corresponding to the consumption of fossil fuels but rather, they evaluate the area needed for the production of renewable energy carriers which are suitable for substituting fossil fuels (Stöglehner, 2003). Emergy analysis, on the other hand, overcomes the shortcomings of these existing approaches. The most attractive characteristic of emergy analysis is that its common unit allows all resources to be compared on a fair basis. In the conventional calculation of ecological footprint, an indirect weighing system is used to translate different pressures into an amount of land. We have used emergy as the common unit, thus avoiding the controversial topic of yields in the calculation of energy footprints. This means that an area based on emergy analysis will give a more realistic picture of the ecological footprint.

The conventional calculation of carrying capacity refers only to land that is “ecologically productive for human purposes” and excludes, for example, deserts and ice caps (Wackernagel and Rees, 1996). However, deciding which areas of land to exclude can be arbitrary. Even land in extreme environments can be useful, directly or indirectly, for human purposes. Many indirect human benefits of biodiversity or other ecosystem attributes present in these environments are not known. Hence, when calculating using the conventional approach, these areas of land should not be disregarded. In our calculations of carrying capacity, we have therefore considered all areas of land. That is why, in case of Gansu province, our calculation of carrying capacity is larger than the conventional calculation.

A major advantage with emergy analysis is the possibility of measuring resource use of ecosystems. It has to be acknowledged, however, that the complexity of ecosystems will always make calculations of transformities difficult and uncertain. There is no single transformity for any class of product or process and that when examined in detail, each production pathway for any given product represents a unique transformation process that will result in a different transformity. This will affect the reliability of conclusions at high levels of detail. The emergy analysis is developed out of theories in ecosystem ecology. Some of these theories are new and controversial hypotheses. Only further research involving emergy analysis and system principles will verify the solidity of our modified calculations.

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