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Ecological footprint of the Chinese population, environment and development

CHEN DONGJING*, CHENG GUODONG, XU ZHONGMIN AND ZHANG ZHIQIANG
State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute,
Chinese Academy of Sciences, No. 260, Donggang West Road, Lanzhou, 730000, P.R. China

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SUMMARY

The ecological footprint (EF) can be used to investigate relationships between population, environment and development. In China, the per caput EF is estimated to have increased by 83% between 1981 (0.82 ha caput^{-1}) and 2000 (1.49 ha caput^{-1}), to about 1.31 times China's area (including its oceanic territory), while the ecological deficit increased from 0.066 ha caput^{-1} in 1981 to 0.735 ha caput^{-1} in 2000. Over this period, the proportions of six sub-footprint types have changed considerably: the percentages of arable, fossil energy and forest land decreased from 44.8%, 41.5% and 4.1% to 27.1%, 40.1% and 3.0%, respectively; while sea, pasture and built-up land percentages increased from 3.8%, 4.4% and 1.3% to 15.2%, 12.4% and 2.2%, respectively. The production coefficients of gross domestic product (GDP) to the EF of China increased from 584 RMB ha^{-1} in 1981, to 1522 RMB ha^{-1} in 2000, reflecting an increasing efficiency in resource use. The EF correlates positively with disposable income and expenditure, which can be described by income and expenditure elasticity. Some measures are suggested to decrease the Chinese ecological deficit on the road to sustainability.

Keywords: biocapacity, ecological footprint, expenditure elasticity, income elasticity, production coefficient, gross domestic product, sustainable development, China

INTRODUCTION

Sustainable development requires that the human exploitation of natural resources and ecosystem services does not exceed the renewal capacity of the Earth's biosphere; there is a requirement, therefore, to measure the human pressure on the environment (World Commission on Environment and Development 1987). Many efforts have been made since the 1960s to measure the human pressure (Meadows *et al.* 1972; Holdren & Ehrlich 1974; Lieth & Whittaker 1975; Odum 1994). Progress includes: assessment of human use of the net primary productivity of the biosphere (Vitousek *et al.* 1986), evaluation of system energy (Pimentel *et al.* 1994), the sustainable process index (Krotscheck & Narodoslawsy 1996), socio-ecological indicators (Azar *et al.* 1996), evaluation of ecosystem services (Costanza *et al.* 1997) and the ecological footprint (EF; Wackernagel & Rees 1996). All these studies aim quantitatively to reflect the use of natural resources and environmental services, and, as a result, allow us to become conscious of human impact on the environment and consequently reduce the negative effects.

Wackernagel and Rees (1996) defined the EF as the total amount of ecologically productive land required to support the consumption of, and absorb the waste generated, by a given population. Every individual, process, activity or region has an impact on the Earth, via resource use, waste generation and use of services provided by the environment. These impacts can be converted into a biologically productive area of land required to support the activities. By comparing the human impacts with the productive area provided by the environment, it can be determined whether or not human pressure is within the carrying capacity of the environment. The EF can clearly show the consequences of increasing consumption patterns and trade, and the distribution of natural resources accessibility, and help elucidate the issue of geographical reallocation of environmental pressure.

Considerable attention has been paid to the application of the EF in both developed and developing countries. The EF has been widely used to evaluate resource use at different levels from those of individual, city and country to global scales (see Wackernagel & Rees 1996; Folke *et al.* 1997; Bicknell *et al.* 1998; Wackernagel *et al.* 1999; Lenzen & Murray 2001). Many countries have exceeded their locally available biocapacity (Wackernagel & Rees 1996; Wackernagel *et al.* 1999). A study by Folke *et al.* (1997) indicated that the EFs of megalopolises around the Baltic Sea were far larger than those of their territories. Bicknell *et al.* (1998) calculated the EF of New Zealand with a modified form of input-output analysis. By 2000, Xu *et al.* (2000) had undertaken a case study of the EF of China. This method of evaluating sustainable development has generated considerable interest and discussion. Advocates of the approach state that the EF is a way to establish perception of social dependence on ecosystem support and it can provide a reasonable level of detail for the policy maker (see Constanza 2000; Deutsch *et al.* 2000; Templet 2000). But some people have criticized the EF concept and method (van den Bergh & Verbruggen 1999; van Kooten & Bulte 2000) for

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*Correspondence: Dr Professor Chen Dongjing, Department of International Business and Economics, Qingdao University, Qingdao, China, Tel: +86 532 5953 733 e-mail: cdongj@163.net

its main two weaknesses, namely that the method does not capture the full range of ecologically significant impact on the ecosphere and it is excessively simple.

China is a developing country that boasts the largest land area and the highest national population. The population reached 1.266 billion by the end of 2000. The economy of China has also been growing rapidly. In the last 20 years, the annual growth rate in the GDP of China has generally remained above 8%. The GDP in 2000 was six times that of 1981 (based on the 1980 price). Living standards improved considerably over the same period. The annual income per caput was 440% higher in 2000 than that in 1981. However, as a consequence of the immense population of China and the low level of production, China has achieved remarkable economic growth only by sacrificing its environmental resources; land quality has been seriously degraded, desertification has increased, and air and water have become severely polluted. With population increase, available resources per caput have been decreasing; for example, available land per caput has decreased from 1.05 ha in 1981 to 0.87 ha in 2000, resulting in arable land per caput decreasing from 0.15 ha in 1981 to 0.1 ha in 2000. The declining environmental situation hinders China's economic development. It is clear that one of the key problems confronting China is the conflict between economic development and the carrying capacity of the environment. The goal of this paper was to investigate the pressure from resource use and economic development on the environment both within and outwith the country. To do this, we estimated the annual EF of China for the period 1981–2000, and we derived the EF index, biocapacity, ecological deficit, ratio of GDP to EF and relationships between EFs, household income and expenditure.

METHODS

Wackernagel and Rees (1996) attributed the consumption of various resources to arable, pasture, forest, fossil energy land, built-up land and the sea. Calculating the per caput EF of China was a multi-stage process, which can be expressed as the equation:

$$\begin{aligned} ef &= \sum r_i AA_i = \sum r_i (C_i / Y_i) \\ &= \sum r_i (P_i + I_i - E_i)/(Y_i \times N), \end{aligned} \tag{1}$$

where, ef is the ecological footprint per caput, AA_i is the biologically productive land area converted from consumed commodity i, Y_i is the world average yield per hectare of consumed commodity i, C_i is per caput consumption volume of commodity i, P_i, I_i and E_i are total domestic output, import and export volumes of commodity i, respectively, r_i is the equivalence factor which translates the specific land use into a generic biologically productive area by adjusting for biomass productivity, and N is the number of people in the population in a given year.

In the equation, r_i reflects the relationship between the world average yield per hectare of i biologically productive land and world average yield per hectare of all types of biologically productive land. The equivalence factor of 2.8 for arable land, for example, indicates that the world average yield per hectare of arable land is 2.8 times that of all types of biologically productive land in the world. The role of the equivalence factor is to translate various land types with different productive yields per hectare into a type of land with the same productive yield per hectare so as to compare various biologically productive land areas. The equivalence factors of six types of land suggested by Wackernagel and Rees (1996) were 2.8 for arable and built-up land, 0.5 for pasture, 1.1 for forest and fossil energy land and 0.2 for the sea. The product of N and ef is the total EF of the country. Equation (1) shows that the EF is a function of population and consumed bioresources per caput. The EF can change with change in population size and/or consumption level. The EF can help to assess the pressure exerted by a local community on the environment, and thus assess how consumption affects the sustainable development of a country, a region, or even the whole world.

The biologically productive area can represent the capacity of resources and services provided by a regional environment. The biocapacity per caput of the area can be calculated as follows:

$$bc = \sum a_i r_i y_i = \sum A_i r_i y_i / N, \tag{2}$$

where, bc is biocapacity per caput, a_i is per caput area of biologically productive land i in the locality, A_i is the total area of biologically productive land i in the locality, r_i is the equivalence factor (see Eq. 1), y_i is a yield factor that reflects the relationship between the local yield per hectare and the world average yield per caput of various lands and N is population in a particular year. If $y_i = 1.2$ this signifies that the local yield of biologically productive land i is 1.2 times the world average yield of i. Productivity of land is comprehensively influenced by human management factors (including operation type, technology and knowledge) and by natural circumstances (including soils and climate). Therefore in order to make valid comparisons, yield factors should be adjusted with time. Over the last 20 years, land productivity has changed dramatically in China (Board of China Agricultural Yearbook 1982–2001). To make a meaningful comparison, therefore, the yield factors were adjusted from year to year based on the per hectare world average yield of six types of biologically productive land in 1993 (Wackernagel & Rees 1996; Wackernagel *et al.* 1999).

By comparing ef with bc, we calculated the ecological deficit that appears when the EF is larger than the local biocapacity or the ecological surplus that appears when the EF is smaller than the local biocapacity. The ecological deficit/surplus combined with socio-economic considerations indicates whether a country, in principle, is able to support itself by domestic

Table 1 The ecological footprint of China 1981–2000. US$ 1 = 8.3 RMB in 2003.

Year	*Population (10^8)*	*GDP (10^8 1980 price)*	*EF (ha caput^{-1})*	*bc (ha caput^{-1})*	*Ecological deficit (ha caput^{-1})*	*GDP yield coefficient of EF (RMB ha^{-1})*	*Total EF (10^6ha)*	*Total biocapacity (10^6ha)*	*Total ecological deficit (10^6ha)*
1981	9.96	4751.48	0.817	0.751	−0.066	583.9	813.70	748.07	−65.63
1982	10.15	5183.79	0.853	0.756	−0.097	598.8	865.68	767.26	−98.42
1983	10.25	5748.51	0.903	0.782	−0.121	620.8	925.97	801.80	−124.17
1984	10.35	6620.91	0.962	0.751	−0.210	665.3	995.14	777.47	−217.67
1985	10.59	7512.79	0.957	0.657	−0.299	742.0	1012.51	695.90	−316.61
1986	10.75	8178.78	1.037	0.642	−0.395	733.4	1115.21	690.39	−424.83
1987	10.93	9125.18	1.070	0.640	−0.429	780.6	1169.05	699.97	−469.08
1988	11.10	10153.37	1.071	0.630	−0.442	853.8	1189.20	698.96	−490.24
1989	11.27	10566.20	1.083	0.632	−0.452	865.5	1220.80	711.84	−508.96
1990	11.43	10971.24	1.137	0.640	−0.497	843.8	1300.25	732.05	−568.21
1991	11.58	11979.96	1.213	0.657	−0.556	852.8	1404.73	761.26	−643.47
1992	11.72	13685.82	1.249	0.661	−0.589	934.9	1463.90	774.25	−689.65
1993	11.85	15531.88	1.246	0.665	−0.581	1051.8	1476.65	788.65	−688.00
1994	11.99	17498.69	1.311	0.653	−0.658	1113.6	1571.38	782.33	−789.06
1995	12.11	19336.96	1.445	0.659	−0.786	1105.0	1749.93	797.89	−952.04
1996	12.24	21190.82	1.513	0.670	−0.842	1144.6	1851.44	820.41	−1031.04
1997	12.36	23064.15	1.521	0.658	−0.863	1226.2	1880.91	813.49	−1067.42
1998	12.48	24863.48	1.507	0.662	−0.845	1322.1	1880.61	825.91	−1054.70
1999	12.59	26627.76	1.492	0.779	−0.713	1417.6	1878.34	980.88	−897.46
2000	12.66	28773.71	1.493	0.759	−0.735	1522.1	1890.34	960.21	−930.13

resources or whether it has to import resources. A 12% area has been deducted from the calculated biocapacity to protect the biodiversity of the Earth (Wackernagel & Rees 1996).

We consulted Chinese government statistics (Board of China Agricultural Yearbook 1982–2001; China Statistical Bureau 1982–2001) to calculate the EF and other indicators for China.

RESULTS

The EF of China

The EF per caput of China has increased over the last 20 years, being 0.82 ha in 1981 and 1.49 ha in 2000 (Table 1). The EF per caput in 1997 (1.52 ha) was the largest for the 20-year period. The increase in the EF per caput reflects the increase in consumption of bioresources per caput and changes in living standards with social and economic development. The six components of the EF per caput have been enhanced in similar ways. In 2000, the EFs of sea and pasture were, respectively, 628% and 409% larger than in 1981 (Table 2). Fossil energy land and arable land are the two types of land with the highest demand, the average figures for 1981–2000 being 0.51 ha and 0.42 ha, respectively. Analysis of the six land types as proportions of the EF showed that arable, fossil energy and forest land decreased from 44.8%, 41.5% and 4.1% in 1981 to 27.1%, 40.1% and 3.0% in 2000, respectively. Conversely, the proportion of sea, pasture and built-up land increased from 3.8%, 4.4% and 1.3% in 1981 to 15.2%, 12.4% and 2.2% in 2000. These changes have resulted from the population changing to a more meat and seafood-based diet and increasing demands for living space.

The total EF is the product of population and *ef*. With the increase in population size and *ef*, total EF is also increasing (Table 1). The total EF has increased 130%, from 8.14 million km^2 in 1981 to 18.90 million km^2 in 2000, and the total EF area is 1.31 times the total land area of 14.43 million km^2 (inclusive of 4.73 million km^2 sea area; Zhang *et al.* 2001).

Biocapacity of China

The per caput biocapacity of China changed little during 1981–2000 (Table 1), the average figure being 0.685 ha caput^{-1}. The reason for this is that the enhancement of land productivity was partly counteracted by the increase in population and degradation of land. For example, the average yield per hectare of cereals for arable land in China increased from 2827.5 kg ha^{-1} in 1981 to 4785 kg ha^{-1} in 2000 (the average annual growth rate being 2.7%), but the population increased from 0.996 billion in 1981 to 1.266 billion in 2000 (the growth rate being 1.3%) (Board of China Agricultural Yearbook 1982–2001; China Statistical Bureau 1982–2001). From 1981–1988, the trend of the biocapacity per caput to decrease indicated that the growth rate of land productivity was less than the rate of population increase and land degradation.

The total biocapacity tended first to decrease and then increase during 1981–2000 (Table 1). The difference between the highest total biocapacity in 1999 (9.809 million km^2) and the smallest total biocapacity in 1986 (6.904 million km^2) was 2.905 million km^2. In 1999 the value was 44.08% higher than the 1986 value.

Table 2 Components (ha $caput^{-1}$) of the ecological footprint of China, 1981–2000.

Year	*Arable land*	*Pasture*	*Forest land*	*Fossil energy land*	*Built-up land*	*Sea*	*Total*
1981	0.366	0.036	0.034	0.339	0.010	0.031	0.817
1982	0.395	0.031	0.034	0.348	0.011	0.034	0.853
1983	0.418	0.035	0.036	0.367	0.011	0.036	0.903
1984	0.438	0.037	0.042	0.393	0.012	0.040	0.962
1985	0.396	0.045	0.043	0.415	0.013	0.045	0.957
1986	0.449	0.057	0.042	0.422	0.014	0.052	1.037
1987	0.437	0.058	0.042	0.458	0.015	0.059	1.070
1988	0.394	0.069	0.042	0.485	0.017	0.064	1.071
1989	0.415	0.071	0.039	0.472	0.017	0.069	1.083
1990	0.435	0.075	0.036	0.501	0.018	0.072	1.137
1991	0.425	0.086	0.037	0.567	0.020	0.078	1.213
1992	0.419	0.095	0.040	0.585	0.022	0.089	1.249
1993	0.419	0.107	0.041	0.551	0.024	0.103	1.246
1994	0.414	0.131	0.043	0.577	0.026	0.120	1.311
1995	0.449	0.155	0.046	0.624	0.031	0.140	1.445
1996	0.468	0.140	0.046	0.648	0.030	0.182	1.513
1997	0.448	0.170	0.046	0.629	0.031	0.197	1.521
1998	0.453	0.166	0.044	0.601	0.031	0.211	1.507
1999	0.445	0.173	0.041	0.580	0.033	0.220	1.492
2000	0.405	0.185	0.045	0.599	0.033	0.227	1.493

Table 3 Regressions relating the GDP to the EF, and the EF to disposable income and expenditure (1980 prices).

Independent variable	*Dependent variable*	*Equation*	R^2	p
EF (ha $caput^{-1}$)	GDP (10^3 RMB $caput^{-1}$)	$GDP_{EF} = 0.7EF^{2.358}$	0.97	< 0.05
Income (10^3 RMB $caput^{-1}$)	EF (ha $caput^{-1}$)	$F_I = 1.5I^{0.467}$	0.95	< 0.001
Expenditure (10^3 RMB $caput^{-1}$)	EF (ha $caput^{-1}$)	$F_E = 1.6E^{0.428}$	0.96	< 0.001

Ecological deficit

The ecological deficit in China increased greatly during the period 1981–2000. The per caput ecological deficit and total ecological deficit in 2000 were 11 times and 14 times those of 1981, respectively; the largest ecological deficit per caput of 0.863 ha $caput^{-1}$ and the largest total ecological deficit of 10.674 million km^2 were both in 1997 (Table 1). Since 1994, the ecological deficit per caput (0.658 ha $caput^{-1}$) and total ecological deficit (7.891 million km^2) of China have exceeded domestic per caput biocapacity (0.653 ha $caput^{-1}$) and total biocapacity (7.823 million km^2), respectively.

GDP:EF ratio

The ratio (production or yield coefficient) between GDP per caput and the EF per caput in a given year can be used as a measure of efficiency of resource use; the higher the coefficient, the higher is the efficiency of resource use. The EF GDP yield coefficient of China increased steadily over the 20-year period, almost doubling from 584 RMB ha^{-1} in 1981 to 1522 RMB ha^{-1} in 2000 (Table 1; US\$ 1 = 8.3 RMB in 2003). Per caput GDP and EF have shown a strong significant positive correlation ($R^2 = 0.97$; $p < 0.05$) (Fig. 1, Table 3).

The relationship between EF, household income and expenditure

In order to learn more about the characteristics of EF change, we investigated the influence of demographic variables, disposable income and expenditure on the EF per caput. There were strong positive correlations between EF and disposable income ($R_I^2 = 0.95$; Fig. 2) and expenditure per caput ($R_E^2 = 0.96$; Fig. 3), indicating that the EF was increasing with increase in either disposable income or expenditure. The EF income elasticity coefficient (η_I) and expenditure elasticity coefficient (η_E) (Table 3) are exponents in the regression formulae. That is to say, $\eta_I = 0.476$ and

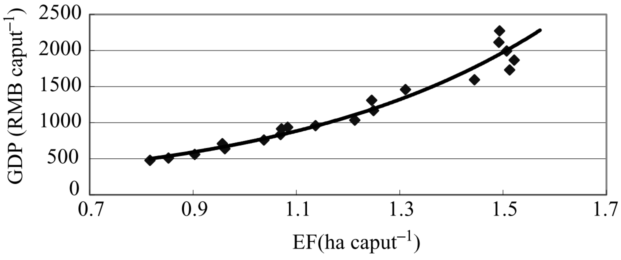

Figure 1 Relationship between China's GDP and EF over the period 1981–2000.

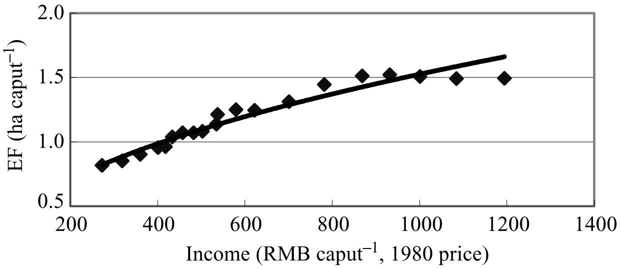

Figure 2 Relationship between the EF and income, based on the EF per caput (Table 1) and the income per caput adjusted to 1980s prices (data from China Statistical Bureau 1982–2001).

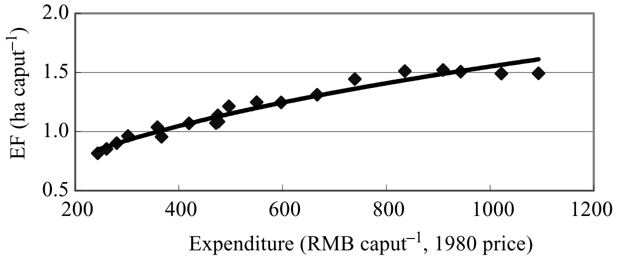

Figure 3 Relationship between the EF and expenditure (data from China Statistical Bureau 1982–2001).

$\eta_E = 0.428$, meaning that, for an income increase of 10%, the EF per caput increased by 4.76%; thus the demand for resources increased by 4.76%. With an increase in expenditure of 10%, the EF per caput increased by 4.28%, and demand for resources therefore also increased by 4.28%. The relationships between EF, income and expenditure indicate that with increased household income and expenditure, increase in the demand for resources will have exerted greater pressure on the environment in China.

DISCUSSION

This study shows that Chinese consumption structure and level have changed significantly during the 20-year period, 1981–2000. The total EF steadily increased, indicating that Chinese people were consuming more and more natural resources and ecosystem services, placing a pressure on the environment incompatible with sustainable development in China. Currently, the domestic biocapacity in China is less than the world average (1.8 ha caput^{-1}; Wackernagel & Rees 1996); and it is far less than many developed countries such as New Zealand (14.3 ha caput^{-1}), USA (6.2 ha caput^{-1}) and Canada (8.5 ha caput^{-1}). Chinese ecological deficits indicate that the Chinese have been becoming more dependent on the capacity of other nations' ecosystems and/or they have been excessively exploiting domestic natural resources and services. These may be the only two means to meet human consumption in China, and both may be harmful to environmental protection and sustainable development both nationally and internationally. But the ratio of GDP to the EF indicates that although the impact on the environment in China has been increasing constantly, the efficiency of use of resources has also continually improved, its growth rate being larger than that of the EF per caput.

According to our results, policies and measures to decrease the ecological deficit are urgently required to reduce the chances that Chinese people will unsustainably consume stocks of natural resources and services. To address this imbalance, Wackernagel *et al.* (1999) and Vuuren and Smeets (2000) have suggested three policies to reduce deficits. These include: improving the yield capacity by preventing the degradation of land; changing the consumption patterns so as to avoid excessive fishing, deforestation and destruction of pasture; and improving energy use efficiency through developing renewable energy resources including solar, wind and tidal energy, to decrease the emission of pollutants and consumption of fossil energy land. To achieve these goals in China, two areas for consideration are to effectively control population size and increase the yield of productive land by enhancing input to available land. World improvements of land (especially agricultural land) productivity have on the whole come at the cost of increased soil erosion, salinization of the soil profile, loss of biodiversity, and increased inputs of artificial fertilizers and biocides (Matson *et al.* 1997; Vitousek *et al.* 1997; Chapin *et al.* 2000), which implies that the increase in (agricultural) land productivity has resulted in a massive increase in the sector's EF. China faces a big challenge on the road to sustainable development.

The calculated per caput EF in China is likely to be smaller than the real figure to some extent, due to the omission of the biologically productive land area needed for assimilation and decomposition of wastes in the calculation, the EF of some smaller elements of consumption of raw materials which are not reflected in the statistics and the omitted EF of water resources which are crucial to arid regions. Due to different data sources and yield adjustment factors, it is inevitable that there are differences from other studies. The EF has, however, highlighted the pressure on the environment exerted by population increase, economic development and people's consumption in China during 1981–2000.

The EF approach places emphasis particularly on the evaluation of pressure exerted by human development on local natural resources and ecosystem services. It has given a new dimension to research on sustainable development and can be used to evaluate impact of current human activities on the environment, but cannot predict a regional development trend (Rees 2000). The technique needs to be combined with other indicators (such as economic and social) and consider the relative balance of economic development, equal distribution of social benefits and efficient use of economic resources (Chen *et al.* 2001). Although there are weaknesses to be addressed, the EF is an intuitively simple framework to reflect the relationship between human society and the environment on which it depends.

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