An effect analysis of changes in the composition of the water ecological footprint in Jiangyin City, China

Dan Hu¹, Feng Li¹, Bennan Wang¹, Kampeng Lei², Aixin Cao², Zhen Wang¹ and Lin Yin-Hua³

¹State Key Laboratory of Urban & Regional Ecology, Research Center for Eco-environmental Sciences, Chinese Academy of Sciences, Beijing, China

²Faculty of Science and Technology, University of Macao, MSAR, China

³Chinese Academy of Forestry Sciences, Beijing, China

Key words: Water ecological footprint, freshwater ecosystems, sensitivity test

SUMMARY

Ecological footprint (EF) analysis is an effective tool to assess ecosystem appropriation, but weaknesses still exist. In order to estimate a city's ecosystem appropriation, we made two modifications to EF: 1) including different types of freshwater area in the calculating framework; and 2) re-adjusting all equivalent factors in terms of different types of freshwater. The modifications are mainly concerned with changes in the composition of freshwater areas in EF analysis; that is, the proportion of aquaculture freshwater and tap freshwater. An assumption of 25% of aquaculture freshwater was used to conduct a sensitivity test. It shows that variation of the proportion leads to different equivalent and yield factors for tap freshwater areas. The variations not only changes the EF of freshwater but also the total EF. The modified EF calculation served to assess ecosystem appropriation in Jiangyin city in 1998. By comparing the original and the modified EF, it was found that the ecological deficit was larger (2.19 ha per capita) in the modified calculation than in the original (2.16 ha per capita). The original calculation is an underestimate because direct consumption of freshwater was not fully included in its calculating framework. From the modified calculation, the EF for different categories of ecosystems decreased, from fossil energy land, arable land and pasture to built-up areas, which together occupy about 97.58% of the total EF. Fossil energy land occupied 68.55% of the total, while freshwater areas took only 0.62%. The main ecological deficits were from fossil energy land, arable land, pasture and marine areas. Ecological supply is lacking within Jiangyin and relies on ecosystems outside the city to survive. Ecosystem management is indispensable to optimise the efficiency of ecosystem use and to expand the biological capacity of the city. The modified EF could provide a more reasonable instrument in policy-making and implementing sustainable management of ecosystems.

INTRODUCTION

Ecosystem appropriation has become an important topic in the last 10 years. Its involves two

approaches: (1) estimating the appropriation of ecosystems on a physical scale of mass or energy

Correspondence: Feng Li, State Key Laboratory of Urban & Regional Ecology, Research Center for Eco-environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China. E-mail: lifeng@rcees.ac.cn or hrcees@vip.sina.com

flows (Vitousek *et al.* 1986; Postel *et al.* 1996), and (2) estimating the appropriation of ecosystems at spatial scales, such as the ecological footprint (EF) (Wackernagel and Rees 1996; Wackernagel *et al.* 1999a,b; Lasson *et al.* 1994; Hu 2000; Deutsch *et al.* 2000). The spatial-based approach indicates ecosystem appropriation using the bio-productive land area. This approach has two obvious advantages: (1) simplicity in calculation, and (2) high applicability in human–environmental interaction analysis. The method also has some obvious weaknesses and has received criticism (van den Bergh and Verbruggen 1999; van den Bergh *et al.* 1999; van Kooten and Bulte 2000; Rees 2000; Ayres 2000) and some modification (Jansson *et al.* 1999, Rees 2000; Simmons and Lewis 2000; Haberl *et al.* 2001; Lenzen *et al.* 2001; Hu 2002). The improvements focus on: (1) including more categories of ecosystems, such as freshwater areas and other ecosystems with very low bioproductivity, adding them to component-based or land disturbance-based real areas, or leaving them in individual categories of land but aggregating them by weights of bioproductivity (Folke *et al.* 1997; Deutsch *et al.* 2000; Simmons and Lewis 2000; Lenzen *et al.* 2001); (2) introducing other techniques of flux analysis for mass and energy, such as input–output analysis, into the calculation (Lenzen *et al.* 2001); (3) including more greenhouse gas emissions other than CO₂ into EF analysis (Lenzen *et al.* 2001); and (4) injecting fisheries and biomass substitution into the calculation (Wackernagel *et al.* 2005).

In this paper, we have modified the calculation of the freshwater EF based on the original

calculation framework proposed by Wackernagel and colleagues (Wackernagel and Rees 1996; Wackernagel *et al.* 1999a,b), making it more applicable for different conditions. The focus of our modification is to include two different types of freshwater areas (areas of aquaculture freshwater and tap freshwater) into the EF calculation. In addition, a case study using the modified method provides a comparison of the difference in results between the original and the modified calculation. Finally, a sensitivity test served to examine how changes in the composition of freshwater areas, expressed as the proportion of the two types of freshwater areas, influences the results of EF calculation.

Ecosystem appropriation in Jiangyin in recent decades

Jiangyin is on the south bank of the Yangtze River – the largest river in China. The high proportion of water areas in its territory plays a crucial role in its development, and water ecosystem appropriation is one of the main factors affecting its natural pattern of ecosystems services (Figure 1). Jiangyin became an administrative municipality in 1987 and, since then, there has been enormous ecosystem appropriation caused by urban development. Scarcity in ecosystems services has become very severe, creating a special challenge for ecosystems management, where rapid urban development has caused an obvious reduction in the size of natural ecosystems in the last 30 years (Table 1). From 1990 to 1998, the area of urban areas increased by

Figure 1 Location of Jiangyin city in China

Table 1 Changes in the area of appropriated forest ecosystems driven by urban expansion in Jiangyin city from 1950 to 1998

Period	1950–1960	1970–1980	1980–1990	1990–1998
Total urban area (ha)	–	632.89	338.92	2248.06
Forest area (ha)	1386.44 (+)	555.12 (–)	1176.95 (+)	334.69 (–)
Annual appropriation rate (ha y ^{–1})	–	63.3	33.9	224.8

Note: + expresses an increase in forests, – refers to a decrease in forests. Data cited from Jiangyin Land Chorography 1998 and Jiangyin Statistical Yearbook 1998

1909.1 ha, with an annual appropriation rate of about 224.8 ha per year, much higher than that of the previous two decades. As the city has expanded, arable land per capita has decreased from 0.05 ha in 1980 to 0.04 ha in 1998 (Statistical Bureau of Jiangyin 1998). Many natural ecosystems have become built-up areas, and forest ecosystems have suffered a huge decline from 1980 to 1998.

The city covers 98 300 ha, with a population of 1.14 million. Its GDP is 27.22 billion yuan (US\$1 = 8.0 yuan), about 23810 yuan per capita in 1998 (Statistical Bureau of Jiangyin 1998), increasing from 624 yuan in 1980 to 7564 yuan in 1998 (at 1980 price level).

METHODS

The original framework of EF calculation

The first step in EF calculation for a given administrative area is to estimate the per capita area of appropriated ecosystems (aa) with the provision of *i*th item of major products or services by dividing average annual consumption of *i*th item ('*c*' in kg per capita) by its average annual productivity or yield ('*p*' in kg/ha):

$$aa_i = c_i / p_i$$

In practice, it is often only possible to estimate per capita consumption by dividing aggregate consumption by total population (*N*). Of course, many items of consumption (e.g. clothing and furniture) come from several inputs and it is useful to separately estimate the area appropriated by each significant input. The total per capita EF ('*ef*') can then be calculated by summing all areas of ecosystems appropriated by individual items in the annual shopping basket of goods and services:

$$EF = N[ef = \sum(aa_i) = \sum(c_i / p_i)]$$

Thus, EF for a certain size of population is the per capita footprint multiplied by the population size (*N*): $EF = N(ef)$.

It is useful to separate consumption into five major categories: food, housing, transportation, consumer goods and services. These categories can be subdivided as necessary. The 'embodied' energy and raw materials of a commodity is the total quantities of energy and materials used during the life cycle of that commodity, for its manufacture, transport and disposal. 'Energy intensity' refers to the direct embodied energy per unit of a good or service. Similarly, we can speak of the 'embodied EF' of a commodity as its contribution to the consumer EF.

Modified EF calculation

Modification of the original EF calculation is necessary to fully consider EF analysis of freshwater ecosystems. Our proposed modifications are outlined below.

EF of freshwater in the calculation framework

Inland waters add another 0.3 billion ha, giving 2.3 billion ha of potential fisheries out of the 36.6 billion ha of ocean and inland waters on our planet (FAO 1999). The majority of marine fish catches occur on continental shelves, and excluding inaccessible or unproductive waters leaves 2.0 billion ha. Although a fraction of the ocean's 36.3 billion ha, these 2.0 billion ha provide over 95% of marine fish catches (WRI 2000). The fishing footprint assumes additional by-catch according to the species composition of national or local fish catches. Inland water and continental shelf areas have replaced the EEZ (Exclusive Economic Zone) to give a far more accurate distribution of global fishing capacity (Wackernagel *et al.* 2005).

Freshwater areas are important for human survival. They include inland areas such as rivers, lakes, reservoirs and other types of catchment, and differ from other types of ecosystem such as forest, grassland and arable land. As shortage of freshwater is a worldwide problem, freshwater ecosystem appropriation should not be omitted in any EF analysis. Therefore, two types of freshwater are considered in our modification: 1) areas for aquaculture fishery, and 2) areas for water supply to households, industries and capture fishery (abbreviated as tapwater). Agricultural water uses are not included here to avoid double counting, since they are possibly already included in cropland, grassland, forest and so on. The two kinds of freshwater area obviously differ from each other in bioproductivity, and they perform many ecological services for human welfare.

Similar to the original EF calculation, the supply and demand of freshwater ecosystems in terms of spatial area may be obtained according to their equivalent and yield factors. In our calculation, each EF (or the demand for aquaculture and tapwater) is calculated by converting the consumption quantity into freshwater ecosystem area as a global unit, and then summing the numbers (see Appendix I). This separate calculation leads to a higher global equivalent amount of freshwater EF, but a lower equivalent amount of freshwater supply in comparison with estimates from the compound calculation using average values of equivalent and yield factors for freshwater.

Proportion of the two types of freshwater areas

In conducting analysis of water EF, some scholars have included aquaculture freshwater areas; our modifications include both aquaculture and tapwater areas. Additionally, the area of freshwater for aquaculture is assumed to be approximately 25% of the total area of inland freshwater on a global scale; therefore, tapwater area should occupy the other 75%. This hypothesis is applied to calculate global bioproductivities for aquaculture and tapwater.

Fundamental ecological water uses and re-uses of wastewater

The fundamental ecological water uses of freshwater are the minimum amount of water used to

sustain the stability and resilience of local freshwater ecosystems (including their biodiversity). Wackernagel *et al.* (2005) suggested that 12% of the global surface is required for the other 30 million species on Earth, but he did not clearly specify the requirements for freshwater ecosystems maintenance and is possibly an underestimate of real water demand in freshwater ecosystems. Therefore, the concept of fundamental ecological water uses is introduced to estimate the actual amount required for freshwater ecosystem maintenance including hydro-biodiversity conservation. Our EF calculation assumed that 25% of the available freshwater (not the area of freshwater) is conserved for fundamental ecological water uses. The actual area needed for freshwater ecosystem maintenance can be determined from basic data on local hydrological balance and is approximately 12% of the local freshwater area. In our calculation, the amount of local fundamental ecological water uses is deducted from the total available local water stock. In addition, the reuse ratio of wastewater was determined to be 40% for living and industrial uses, according to statistical data for Jiangyin city.

Adjustments to the parameters of equivalence factors for global bioproductive land

According to Wackernagel and colleagues (2005), equivalence factors represent the world average potential productivity of a given bioproductive area relative to the world average potential productivity of all bioproductive areas. For example, the equivalence factor for crops describes potential biomass output attainable in an area with an assumed level of inputs, such as water and fertiliser. Cropland is more productive than rangeland or pasture, so it has a larger value for the equivalence factor than pasture. The equivalence factors for cropland, forest, pasture and built-up area in Wackernagel's calculation are derived from the suitability index of the Global Agro-Ecological Zones (GAEZ) in 2000, a spatial model of potential agricultural yields (Wackernagel *et al.* 2005). In this calculation, EF of fisheries was obtained from their capacity to supply animal protein relative to that of grassland.

In terms of the inclusion of two freshwater areas, we readjusted the equivalence factors according to differences in bioproductivity between freshwater and other categories of bioproductive areas. In our calculation, different types of ecosystems were

Table 2 Parameters of equivalence factors for original and modified calculations

Type of ecosystem	Equivalence factor (original)	Equivalence factor (modified)
Fossil energy	1.49	1.53
Arable land for crops	2.06	2.11
Arable land for pasture	0.62	0.64
Pasture	0.30	0.31
Forest	1.49	1.53
Built-up areas	2.06	2.11
Aquaculture	No	0.24
Tap water	No	0.40
Marine areas	1.22	1.26

Note: Calculation of formulae and explanations for adjustments of equivalence factors are given in Appendix I

calculated according to FAO (1999, 2000) and WRI (2000, 2001) original data for agriculture, fisheries and freshwaters. The values of equivalence factors from our modified calculation is very similar to that of Wackernagel, except for marine areas, and differences mainly come from differences in data sources (Table 2). The productivity of global average bioproductive land is lower when freshwater ecosystem appropriation is introduced into the calculating framework (Table 2), since the productivity of freshwater is lower than that of arable land, forest or marine areas. In addition, the equivalence factors for various types of ecosystems are a little higher than that calculated without considering the two types of freshwater areas.

RESULTS AND DISCUSSION

For rapid development of Jiangyin relies on raw materials and energy that come directly or indirectly from natural ecosystems that release waste substances into the surroundings, causing negative effects or even damage to ecosystem service flows. However, the city often lacks necessary economic mechanisms to sustain its ecological service flows, leading to rapid uncontrolled shifts in natural ecosystems to built-up areas that become larger, while natural areas become smaller. Based on statistical data for Jiangyin (Statistical Bureau of Jiangyi, 1998; Jiangyin Land Chorography Compiling Committee 1998), annual ecosystem appropriation for 1998 was estimated by employing modified calculations (available from the authors). The main characteristics of EF in the city are:

1. **Main products:** including products consumed by city residents, such as beef, poultry, eggs, milk, fruit, aquatic products, sugar, cake, edible oil, fat, silk, tea, tobacco, alcoholic drinks, rubber products and timber. Indigenous natural ecosystems cannot provide enough products and raw materials, so some products are imported.
2. **Freshwater:** there is 47.34 million m³ of surface freshwater annually available for the city; the supply of freshwater mainly relies on inflows from the Yangtze River. The annual water imported is 0.83 billion m³, and about 0.32 billion m³ of this freshwater serves households and industries.
3. **Energy:** total energy consumption was 81.26 PJ in 1998, mainly coal, liquid or gas fossil fuels and hydroelectricity, and was imported from outside the city. Energy consumption of fossil fuels was 70.09 PJ, 86.26% of the total. The embodied energy was 1.93 PJ in imported goods and 15.15 PJ in exported goods, and 68.39 PJ in total net import of various products (including energy).

EF of the city from the original calculation

The EF of Jiangyin was calculated from the original calculation (Wackernagel *et al.* 2002, 2005) and the results are shown in Table 3. There was an ecological deficit of 2.16 ha per capita. Types of ecosystems with a deficit are fossil energy land, arable land, pasture, forest, aquaculture and marine areas.

EF of the city from the modified calculation

There was a 2.19-ha ecological deficit per capita, larger than that in the original calculation, and the ecological deficit was in fossil energy land, arable land, pasture, forest, marine areas and aquaculture areas (Table 4). Fossil energy land had the greatest deficit, followed by arable land. The four main types of appropriated ecosystem decreased gradually from fossil energy land, arable land and pasture to built-up area, and occupied 97.58% of the total EF (Table 4). The fractions of appropriated ecosystem components were: fossil energy land 68.55%, arable land 19.56%, pasture 7.64%, forest 0.90%, built-up areas 1.82%, marine areas 0.91% and freshwater areas 0.62% of the total footprint. The main supplies of ecosystems in the city were: arable land

33.90%, built-up areas (originally arable land) 38.01%, and freshwater areas 19.91% (Table 4).

Comparison of EF analysis between the modified and original calculation

The introduction of freshwater, especially tapwater, into the EF calculation framework changed the equivalent factors and yield factors, and thus made the results of EF calculation different (Table 5). The demand and supply per capita increased correspondingly, and ecological deficit per capita for all types of ecosystem except built-up area also increased in comparison with the original calculation. Therefore, the modified calculation gave higher EF values for supply and ecological deficits.

Table 3 Ecological demand and supply in 1998 with the original calculation

Category	Demand (Footprint) [ha/cap]			Supply (Biocapacity) [ha/cap]		
	Area	Equivalence factor	Equivalence total	Area	Yield factor	Yield adjusted equiv. area
Fossil energy	1.07E + 00	1.49	1.59E + 00	0.00E + 00	1.14	0.00E + 00
Built-up areas	2.06E – 02	2.06	4.23E – 02	2.06E – 02	1.84	7.78E – 02
Arable land	2.21E – 01	2.06	4.54E – 01	1.83E – 02	1.84	6.94E – 02
Pasture	2.87E – 01	0.62	1.77E – 01	2.73E – 02	0.81	1.38E – 02
Forest	1.40E – 02	1.49	2.08E – 02	1.76E – 03	1.14	2.97E – 03
Marine areas	1.72E – 02	1.22	2.10E – 02	0.00E + 00	1.00	0.00E + 00
TOTAL	1.63E + 00		2.3048	TOTAL		1.64E – 01
Total ecological deficit (minus 12% for biodiversity)				TOTAL available		0.1442
						2.1606

Table 4 Ecological demand and supply in Jiangyin in 1998 with the modified calculation

Category	Demand (Footprint) [ha/cap]			Supply (Biocapacity) [ha/cap]		
	Area	Equivalence factor	Equivalence total	Yield factor	Region area	Yield adjusted equiv. area
Fossil energy	1.07E – 01	1.53	1.63E + 00	0.00E + 00	1.14	0.00E + 00
Built-up areas	2.06E – 02	2.11	4.34E – 02	2.06E – 02	1.84	7.99E – 02
Arable land	2.21E – 01	2.11	4.66E – 01	1.83E – 02	1.84	7.13E – 02
Pasture	2.87E – 01	0.64	1.82E – 01	2.73E – 02	0.81	1.41E – 02
Forest	1.40E – 02	1.53	2.14E – 02	1.76E – 03	1.14	3.05E – 03
Marine areas	1.72E – 02	1.26	2.16E – 02	0.00E + 00	1.00	0.00E + 00
Aquaculture	5.90E – 02	0.24	1.40E – 02	9.32E – 03	10.08	1.02E – 02
Tapwater	1.82E – 03	0.40	7.31E – 04	4.25E – 03	8.45	3.17E – 02
TOTAL			2.3840	TOTAL		2.10E – 01
Total ecological deficit (minus 12% for biodiversity)				TOTAL available		0.1901
						2.1939

Table 5 Deviations of EF between the modified and original calculations

<i>Ecosystem category</i>	<i>Deviation in demand [ha/cap]</i>	<i>Deviation in supply [ha/cap]</i>	<i>Deviation in ecological deficit [ha/cap]</i>
Fossil energy	4.44E – 02	0.00E + 00	4.44E – 02
Arable land	1.27E – 02	1.94E – 03	1.07E – 02
Pasture	4.95E – 03	3.85E – 04	4.57E – 03
Forest	5.82E – 04	8.31E – 05	4.98E – 04
Built-up area	1.18E – 03	2.17E – 03	–9.93E – 04
Aquaculture area	–	–	–
Tapwater area	–	–	–
Marine area	5.88E – 04	0.00E + 00	5.88E – 04
Total	0.0792	0.0459	0.0333

Note: Column 4 is the result of the modified calculation minus the original calculation

Sensitivity test for the assumption of 25% included in the modification

The modification to the original EF calculation was based on an important assumption: the area of aquaculture freshwater is about 25% of total inland freshwater. By examining variations in the proportion of aquaculture areas from 15 to 35%, should affect the values of equivalence factors and yield factors; therefore, a sensitivity test was conducted to show how deviation in EF calculation occur. Variation in the equivalence factor for aquaculture areas drops from 66.67% (a deviation of –10%) to –28.57% (a deviation of +10%), and that for tapwater areas declines from –11.76% (a deviation of –10%) to 15.38% (a deviation of +10%). Additionally, variation in the yield factor for aquaculture areas drops from –40.00% (a deviation of –10%) to 40.00% (a deviation of +10%), and variation in the yield factor for tapwater areas decreases from 13.33% (a deviation of –10%) to –13.33% (a deviation of +10%). This showed that the variation relative to the assumption of 25% has a greater effect on the equivalence and yield factors of aquaculture areas than on tapwater areas.

For EF and ecological deficits, variation of per capita EF drops from –0.0036% (a deviation of –10%) to 0.0047% (a deviation of +10%), and variation in per capita supply remains invariant. The variation in per capita deficits drops from –0.0039% (a deviation of –10%) to 0.0051% (a deviation of +10%). This showed that the variation relative to the assumption of 25% has a relatively greater effect on per capita EF or demand and ecological deficits than on per capita supply. However, this effect is quite subtle (less than $\pm 0.01\%$).

CONCLUSIONS

This research proposed modifications to the EF calculation. The modifications mainly dealt with two types of freshwater area into the original calculation. Compared with the original calculation, the modified form produced more appropriation and more ecological deficits, which consequently reflects much more exactly the situation for ecosystem appropriation by the city's development, and so reduces the underestimate. Including two types of freshwater area into the original calculation had an effect on the results of EF calculation. Due to lower productivity of freshwater than some other types of ecosystem, such as arable and forest, the inclusion of two types of freshwater area decreases the productivity of global average bioproductive land; thus, for the other types of ecosystem, the equivalence factors are a little higher than those without considering freshwater.

The change in the proportion between areas of aquaculture and tapwater areas led to variations in equivalence and yield factors for freshwater areas, and had a greater influence on equivalence and yield factors for aquaculture areas than on tapwater areas. The variations relative to the assumption of 25% as the proportion of aquaculture freshwater would not only change the EF of freshwater areas but also the total EF of the city, although not the supply of freshwater to the city. However, the influences of the variations relative to the assumption of 25% are not great.

Jiangyin's development has exerted great pressure on local ecosystems and greater dependence on external resources in maintaining the city's development. To advance the capacity of ecosystems

services, ecosystems management is indispensable for the city to optimise the spatial distribution of ecosystem uses and enhance their efficiency (van den Bergh *et al.* 1999, Hu 1998, 2002; Wackernagel *et al.* 1999a, 2002). The modified EF calculation offers a better tool to help understand the city's condition in terms of ecosystem appropriation and promotes the implementation of sustainable ecosystems management.

REFERENCES

- Ayres RU. Commentary on the utility of the ecological footprint concept. *Ecological Economics* 2000;32: 347–9
- Bergh van den, JCJM and Verbruggen H. An evaluation of the 'Ecological Footprint': Reply to Wackernagel and Ferguson. *Ecological Economics* 1999;31:319–21
- Bergh van den, JCJM and Verbruggen H. Spatial sustainability, trade and indicators: An evaluation of the 'Ecological Footprint'. *Ecological Economics* 1999;29:61–72
- Deutsch L, Jansson A, Troell M, Rönnbäck P, Folke C and Kautsky N. The 'ecological footprint': communicating human dependence on nature's work. *Ecological Economics* 2000;32:351–5
- FAO. FAOSTAT. <http://faostat.fao.org/>; 1999
- FAO. FAOSTAT. <http://faostat.fao.org/>; 2000
- Folke C, Jansson A, Larsson A and Costanza R. Ecosystems appropriation by cities. *Ambio* 1997;26(3): 167–72
- Haberl H, Erb K-H and Krausmann F. How to calculate and interpret ecological footprints for long periods: the case of Austria 1926–1995. *Ecological Economics* 2001;38:25–45
- Hu D. A theoretical approach to eco-capitals. In: Deng N *et al.* (eds), *Sustainable Development: Humans Care for the Future*. Harbin, China: Heilongjiang Education Press; 1998:285 pp.
- Hu D. *The appropriation of ecosystem assets by urban development in Jiangyin city, Jiangsu Province with Wackernagel's method*. Proceedings of Zhuhai-Macao International Conference on Urban Ecology; 2000:78 pp.
- Hu D. Eco-capital and its services in urbanization. IHDP Update. *Newsletter of the International Human Dimensions Programme on Global Environmental Change* 2002;3:16 pp.
- Jansson A, Folke C, Rockström J and Gordon L. Linking freshwater flows and ecosystem services appropriated by people: the case of the Baltic Sea drainage basin. *Ecosystems* 1999;2:351–66
- Jiangyin Land Chorography Compiling Committee. *Jiangyin land chorography*. Nanjing: Jiangsu People Press; 1998
- Kooten van, CG and Bulte EH. The ecological footprint: useful science or politics? *Ecological Economics* 2000;32:385–9
- Lasson J, Folke C and Kautsky N. Ecological limitations and appropriation of ecosystem support by shrimp farming in Colombia. *Environmental Management* 1994;18(5):663–76
- Lenzen M and Murray SA. A modified ecological footprint method and its application to Australia. *Ecological Economics* 2001;37:229–55
- Postel SL, Daily GC and Ehrlich PR. Human appropriation of renewable freshwater. *Science* 1996;271: 785–8
- Rees WE. Eco-footprint analysis: merits and brickbats. *Ecological Economics* 2000;32(3):371–4
- Simmons C and Lewis K. Two feet – two approaches: a component-based model of ecological footprint. *Ecological Economics* 2000;32(3):375–80
- Statistical Bureau of Jiangyin. *Jiangyin Statistical Yearbook of Jiangyin*. Beijing: China Statistical Publishing House; 1998
- Vitousek PM, Ehrlich PR, Ehrlich AH and Matson PA. Human appropriation of the products of photosynthesis. *BioScience* 36(6):368–73
- Wackernagel M and Rees WE. *Our Ecological Footprint – Reducing Human Impact on the Earth*. Gabriola Island PA: New Society Publishers; 1996
- Wackernagel M, Lewan L and Borgström-Hansson C. Evaluating the use of natural capital with the ecological footprint applications in Sweden and sub-regions. *Ambio* 1999a;28:604–12
- Wackernagel M, Onist L, Bello P *et al.* National natural capital accounting with the ecological footprint concept. *Ecological Economics* 1999b;29: 375–90
- Wackernagel M, Schulz NB, Deumling D *et al.* Tracking the ecological overshoot of the human economy. *PNAS* 2002;99(14):9266–71

Wackernagel M, Monfreda C, Moran D *et al.* National Footprint and Biocapacity Accounts 2005: The underlying calculation method. Global Footprint Network; 2005

WRI. *World Resources 2000–2001 – People and Ecosystems: The Fraying Web of Life*. Washington DC: World Resources Institute; 2000

WRI. *World Resources Report 2000–2001*. Washington DC: World Resources Institute; 2001

Appendix I Explanations for the modified calculation used in EF analysis

1. Equivalence and yield factors for freshwater areas

The calculation processes for equivalence and yield factors were performed according to Wackernagel (1999, 2002, 2005):

Bio-productivity of global average bioproductive areas (kg/ha/yr) = total bioproduction of global average bioproductive areas (kg/yr)/total area of global average bi-productive areas (ha/yr).

Based on the above expression, equivalence and yield factors for inland freshwater areas are:

- 1) Equivalence factor for freshwater areas = bioproductivity of global freshwater areas (kg/ha/yr)/bioproductivity of global average bioproductive areas (kg/ha/yr);
- 2) Equivalence factor for tapwater areas = bioproductivity of global tapwater areas (kg/ha/yr)/bioproductivity of global average bioproductive areas (kg/ha/yr);
- 3) Equivalence factor for aquaculture freshwater areas = bioproductivity of global aquaculture freshwater areas (kg/ha/yr)/bi-productivity of global average bioproductive areas (kg/ha/yr);
- 4) Yield factor for local aquaculture freshwater areas = bioyield of local aquaculture freshwater areas (kg/ha/yr)/bioyield of global aquaculture freshwater areas (kg/ha/yr);
- 5) Yield factor of local tapwater areas = yield of local tapwater areas (kg/ha/yr)/bioyield of global tapwater areas (kg/ha/yr);
- 6) Average water output for global tapwater areas (kg/ha/yr) = total water amount available to global tapwater areas (kg/yr)/total area of global tapwater areas (ha/yr), this value contains fundamental ecological water uses of tapwater areas.

2. Sensitivity test for main parameters and variables of EF calculation

The sensitivity test examines how key parameters and variables of EF calculation, such as equivalence factors, yield factors, demand, supply and deficits change when the assumed value for the area of freshwater for aquaculture is about 25% of the total area of inland freshwater at a global scale vary $\pm 10\%$.

- 1) Variations of equivalence or yield factors relative to the assumed 25%
 = [equivalence or yield factor of any type of freshwater area at the assumed value of any percentage – equivalence or yield factor at the assumed value of 25%] / equivalence or yield factor at the assumed value of 25% *100%.
- 2) Variations of per capita demand, supply and ecological deficits relative to the assumption of 25%
 = [per capita demand, supply and ecological deficits at the assumed value of any percentage – per capita demand, supply and ecological deficits at the assumed value of 25%] / per capita demand, supply and ecological deficits at the assumed value of 25% *100%.

3. EF and supply calculation for freshwater areas in equivalent units

- 1) Per capita EF of aquaculture freshwater areas
 = total local consumption of aquatic products (kg/yr)/bioyield of global aquaculture freshwater areas (kg/ha/yr) * equivalence factor for aquaculture freshwater areas/total local population;
- 2) Per capita EF of tapwater areas

= total local freshwater consumption (kg/yr) average water output for global tapwater areas (kg/ha/yr) * equivalence factor for tapwater areas/total local population;

3) Total per capita EF of freshwater areas

= per capita EF of aquaculture freshwater areas + per capita EF of tapwater areas;

4) Per capita supply of tapwater areas

= total local tapwater areas (ha/yr) * equivalence factor for tapwater areas * yield factor for local tapwater areas/total local population.

4. Calculation of conserved rate of fundamental ecological water uses of freshwater areas

As Wackernagel suggested (1999, 2002, 2005), 12% of bioproductive areas is conserved for biodiversity maintenance in EF calculations, but this is not completely applicable in our case study. In our calculation, when the percentage of freshwater areas actually needed for fundamental ecological water uses (hydro-biodiversity maintenance requirement already included) is less than 12%, this assumption is applicable; but when this value is more than 12%, the assumption is not applicable and the percentage actually needed for local fundamental ecological water uses is adopted.