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An analysis of ecological footprint trade and sustainable carrying capacity of the population in Macao

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Ecological footprint (EF) is a useful tool for exploring human impacts on natural ecosystems and has been widely applied. Until now, an important issue on the relationship between population sustainable carrying capacity and EF trade has rarely been discussed. EF trade can have positive or negative impacts on demand and supply of resources, and often changes the ecological carrying capacity of a country, region or city. This study focused on relationships between population carrying capacity and trade using the EF analysis framework. Taking Macao City as a case study, EFs from 1977 to 2004 were calculated. An ecological economic indicator, EF/US\$1000, was used to analyse relationships between international trade of EF and carrying capacity, and a method for calculating population carrying capacity was also established to compare differences in sustainable populations in other countries. The results indicate that EF trade among countries, regions and cities can make up for shortages of domestic ecological resources and expand the population carrying capacity. In terms of ecological carrying capacity, the developmental status of the population in Macao was weakly sustainable. This research is helpful for a country, region or city to adjust its style of consumption and population size towards a reasonable level of sustainability.

Keywords: ecological footprint; carrying capacity; EF trade; sustainable population; Macao city

Introduction

The concept of ecological footprint (EF) accounts for flows of energy and materials to and from any defined economy and converts these into the corresponding land area required to support the flows and assimilate wastes (Wackernagel and Rees 1996; Wackernagel et al. 2005). It expresses human consumption of energy and renewable resources such as crops, animal products and timber in an equivalent unit of global biologically productive area as global hectares (Monfreda et al. 2004). The EF is regarded as a useful accounting tool that is consistent with ecological principles and can be used to assess human appropriation of ecosystems related to population carrying capacity (Wackernagel and Rees 1996; Chambers et al. 2000). Rees (2000) notes that EF is ‘conceptually related to the embodied energy (emergy) analysis of Howard Odum,’ suggesting that EF has a holistic perspective. EF analyses have been made at different scales, from personal (Redefining Progress 1999), to city (Wackernagel and Rees 1996), regional (Wackernagel and Yount 1998) and country (Bicknell et al. 1998; Brown et al. 2000) and global (WWF 2002), and have also been utilized in assessment of ecological impacts of products and transport (Chambers et al. 2000). Moreover, EF has been applied to assess the impact of organizations and services, ranging from energy and water resources to education (Chambers et al. 2000) as well as the sustainability of food systems and agriculture (Deumling et al. 2003).

Both energy and material suffer irreversible dissipation in all ecological economic processes, and the concept of entropy applied to such processes should be understood in

terms of the generation of increasing energetic and material ‘disorder’ as a by-product of the local creation of cultural and technological ‘order’ or structure (Odum 1994). In terms of trade of EF, trade in any product or service, as a kind of embodied negative entropy among countries or regions, actually refers to net imports of biomass and to sink capacity (Andersson and Lindroth 2001). For example, many flows of products, money and tourists enter Macao City from Mainland China and thus provide the city with a certain carrying capacity. This phenomenon of trade in bio-capacity has been researched in several disciplinary fields, and the trading flows of products or services converted into quantities of emergy or EF to analyse relationships between economic development and ecosystem services (Odum 1996; Fischer-Kowalski 1998; Wackernagel et al. 2005; Hornborg 2006).

Carrying capacity is an important ecological economic notion defined as the maximum population size of a given species that an area can support without reducing its ability to support the same species in the future (Daily and Ehrlich 1992), and further defined broadly in terms of human–ecological interactions as the number of individuals that can be supported in a given area within its limit of supply of natural resources, not degrading the natural, social, cultural and economic conditions for present and future generations (Global Development Research Center 2007). Carrying capacity can be distinguished into biophysical and social carrying capacity, the former being usually greater than the latter (Daily and Ehrlich 1992). Apart for biophysical factors, carrying capacity is also affected by many social factors such as

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discounting, the global commons, technological progress and international trade and needs more attention (Daily and Ehrlich 1992; Cohen 1995). The human carrying capacity depends on the availability of renewable and non-renewable resources, and the contributions of natural and human-made capital to human carrying capacity are more complementary than substitutable (Daily and Ehrlich 1992; Cohen 1995; Sagoff 1995). The two important indicators, maximum sustainable use of resources and maximum sustainable abuse, i.e. the maximal sustainable emission rate of a pollutant, are essential for its estimation (Daily and Ehrlich 1992; Cohen 1995). There are massive uncertainties for the relationships between human carrying capacity and ecosystems services, and a reduction in global economic overgrowth and enhancement of ecosystem resilience is necessary to deal with the uncertainty (Ehrlich 1994; Cohen 1995; Walker 1995).

In this article, we attempt to use an EF-based calculating framework to analyse the relationship between carrying capacity and EF trade, establish an operational method to estimate the population carrying capacity, and assess sustainable population size in Macao City.

Environmental and economic characteristics of Macao

Located to the west of the Pearl River estuary (113°31'33"–113°35'43"E, 22°06'39"–22°13'06"N) (Figure 1), Macao is a mixture of Western and Chinese cultures from the past 400 years. With a population of 465,333, Macao is the most densely populated place in the world, with 16,921 people per km² (Maritime Administration 2005). Macao consists of the Macao Peninsula, Taipa Island, Coloane Island and reclaimed land, covering 27.5 km². The urban area occupies 18 km²; Taipa and Coloane Islands are mainly forested.

Colonized by the Portuguese in the 16th century, Macao was the first European settlement in the Far East. Macao's industry has changed rapidly in the last 30 years; agriculture disappeared 10 years ago, fishery has dwindled because of a decline in marine resources, and manufacturing cannot compete with Mainland China; but tourism has developed and become the core sustaining Macao's economy (Maritime

Administration 2005). Macao is a free port where people, cargo and capital generally flow in and out freely. Macao City possesses several unique attractions, including historical heritage sites such as ancient temples, old residential buildings, forts, and baroque churches, and was recognized as a World Cultural Heritage site in 2005.

The GDP of Macao was 8.27×10^{10} MOP (Macao currency, US\$1 = 8.023 MOP) in 2004. The annual average visitor number is about 35.8 times that of the local population. In Macao, gaming and tourism (abbreviated as tourism) make significant contributions to overall economic development. Gaming tax revenue accounts for 77.8% of total government revenue. About one third of the total labour force is employed in tourism (DSEC 2005).

Methods

General EF calculation method

Calculation of the EF for a population is estimated as the per capita land area appropriated (EF_i) for production of each major item of consumption 'i', by dividing average annual consumption of that item ['c' in kg/capita] by its average annual productivity or yield ['p' in kg/ha] (Wackernagel and Rees 1996; Wackernagel et al. 2005):

$$EF_i = \frac{c_i}{p_i} \quad (1)$$

Total per capita EF can be calculated by summing all ecosystem areas appropriated (Wackernagel and Rees 1996; Wackernagel et al. 2005):

$$ef = \sum EF_i = \sum \left(\frac{C_i}{P_i} \right) \quad (2)$$

Thus, the total EF of a population is the per capita footprint multiplied by population size (N) (Wackernagel and Rees 1996; Wackernagel et al. 2005):

$$EF = N(ef) \quad (3)$$

Figure 1. The location of Macao.

Calculation of EF components

Consumption of biological resources

The EF of consumption of biological resources can be calculated as:

$$EF_i = \frac{P_i + I_i - E_i}{Y_i} \quad (4)$$

where EF_i is the EF of consumption of the i th type of resource, P_i is total production of the i th type of resource (for Macao, this value is zero), I_i and E_i are, respectively, import and export of the i th type of resource, and Y_i is global average yield of the i th type of resource (FAO 2000).

Consumption of energy

The consumption of energy in Macao typically includes coal, gasoline, kerosene, diesel, liquefied petroleum gas (LPG) and heavy oil. Their footprints were calculated by dividing the consumed amount by energy conversion constants in GJ/ha. The values of these energy conversion constants are 55 for coal, 93 for gasoline, kerosene, diesel and heavy oil, and 71 for liquefied petroleum gas (LPG) (Wackernagel and Rees 1996; Wackernagel et al. 2005).

Consumption of industrial products

The 'embodied' energy and resources of any industrial product refers to the total amount of energy and materials used during the life cycle of that product for its manufacture, transport and disposal. The EF of the embodied amount of consumption of resources and energy can be calculated using the following formula, by translating total or per capita consumption into the area amount of fossil land (Wackernagel and Rees 1996):

$$EF_i = \frac{(P_i + I_i - E_i)E_d}{E_f} \quad (5)$$

where EF_i is EF of product i , P_i is total production, I_i and E_i are import and export of product i , E_d is its energy density, and E_f is global energy productivity of fossil land (71 GJ/ha/yr) (Wackernagel and Rees 1996). Data on the energy density of embodied resources and energy are available from the Stockholm Environment Institute (IEA 2004).

Consumption of freshwater

Macao has a large shortage of freshwater resources, and freshwater is supplied by Mainland China. The EF of freshwater in Macao is approximated from the following formula, due to a lack of available data (Lei and Wang 2003):

$$EF_w = M_w \left(\frac{EF_c}{GDP_c} \right) \quad (6)$$

where EF_w is imported amount of freshwater footprint, EF_c is EF of Mainland China, GDP_c refers to China's GDP, and M_w is money paid by Macao for import of freshwater.

EF/money ratio and EF balance by trade

The EF as a measure of the (over-) use of bio-capacity (Forum 2000) can be used to elaborate relations between international trade and ecological sustainability at a national and global level. Proponents of EF recommend the use of national ecological deficits as indicators of sustainable development, and suggest that each nation should develop within its own ecological capacity (Wackernagel and Rees 1997; Ferguson 2001). This has been criticized as an anti-trade bias (van den Bergh and Verbruggen 1999; Costanza 2000); leading to the conclusion that trade is ecologically unfriendly and consequently unsustainable (van den Bergh and Verbruggen 1999; Ayres 2000; van Vuuren and Smeets 2001). However, Andersson and Lindroth (2001) argue that comparison of the EF and bio-capacities of each country provides valuable information on a country's dependence on others and on ecological sustainability of trading. If the EF is greater than the biophysical capacity of its territory, it must either import that extra capacity from other territories, or erode its own ecological capacity (Costanza 2000).

Globally, national EF accounts reveal ecological overshoot on a global scale (Monfreda et al. 2004), and the EF deficit can only be offset by a net economic surplus. The natural capital of a country is not eroded if the ecological deficit is smaller than the sum of its net imports of biomass and sink capacity (both measured in land area) (Andersson and Lindroth 2001). Since trade between countries and regions, is ubiquitous the embodied EF exchanges should be measurable. Therefore, the proposed equation can describe resource overshoot of national, regional or city ecological deficit:

$$\text{Domestic ecological deficit} = EF - \text{Bio-capacity}. \quad (7)$$

Consumption of global resources results in overgrazed pastures, depleted fisheries, degraded forests and accumulation of carbon emissions. Ecological deficits can be balanced through trading or through overuse of domestic resources. The total available area of equivalent land for a population in a given region or country can be expressed as BC (total bio-capacity area of a population), total demand for resources can be denoted as EF (total EF area of a population), and the total available bio-capacity from trading as BC_{trade} (total bio-capacity area of a population by trading). To prevent overuse of land, ecological deficits can be balanced only through trading or net import of the embodied bio-capacity, and this relationship is expressed in formula (8) and Figure 2, where the BC for a region or country is denoted as bullets, BC_{trade} as a hexagon, and EF as a shaded rectangle.

$$BC_{\text{trade}} = EF - BC. \quad (8)$$

From a viewpoint of emergy (Odum 1996), EF is embodied in traded products and trade can be expressed as material flow in the opposite direction to monetary flow. An indicator of the ratio of EF and GDP (total annual economic

Figure 2. Relationships of EF, BC and BC_{trade} in Macao.

output of a country, region or city) is the EF/US\$1000 ratio. Although exchange of goods or services performs equally as money in international trade, the purchased EF is very different in relation to its EF/US\$1000. The following equation gives maximum ability of global EF exchanges for a country, region or city when it exchanges its EF with other regions or countries in international trading:

$$EF_{mex} = (1 - k) GDP (T_{fm}) \quad (9)$$

where T_{fm} refers to EF/US\$1000: (1) the global average EF per US\$1000 with a unit of global ha/k\$ if this region's EF/US\$1000 is smaller than the global EF/US\$1000, implying that its quality of life is higher than the global average, and (2) the regional average EF per US\$1000 with the same unit of global ha/k\$ if this region's EF/US\$1000 is greater than the global EF/US\$1000, meaning that its quality of life is lower than the global average. GDP is gross domestic product of a country, region or city, and the constant k is the E-coefficient that indicates the ratio of total external environmental and ecological costs to its GDP. This value changes for different countries or regions, being usually between 1 and 20%, according research on green GDP accounts in China (SEPAC 2006), so its upper value can be taken as 20%.

The EF_{mex} is the potential maximum trading amount of BC for a country, region or city. According to the definition of strong or weak sustainability (Dellink et al. 1999), if the EF_{mex} is equal to or bigger than the total domestic EF deficit, the area can sustain its population, and sustainability is weak for its economy, or it cannot sustain itself. This expression can be simplified as:

$$BC = EF \text{ Strong sustainable} \quad (10)$$

$$EF_{mex} = EF - BC \text{ Weak sustainable or} \\ \text{low risk of unsustainability} \quad (11)$$

$$EF_{mex} < EF - BC \text{ Unsustainable or} \\ \text{high risk of unsustainability.} \quad (12)$$

EF related carrying capacity of a population

The carrying capacity is the maximum size of a population of a given species that a given area can support indefinitely according to its biomass production and waste assimilation (Catton 1986; Wackernagel and Rees 1996). There is a finite natural carrying capacity (CC) that acts as a limiting factor to the scale of the economy. This may subsequently be extended to address relationships between opening regions and trades that have two patterns of economic scale and CC over time (Figure 3): (1) without trade, i.e. a closed or autarkic system with limited carrying capacity ($CC_{autarky}$), completely dependent on its territory's ecosystems; and (2) with trade, i.e. an open system with changing CC dependent on both its own ecosystems and available trading ($CC_{reality}$). A pattern of 'density-dependent growth', where the growth rate is dependent on stock and restrained by some limiting factor of resources, is represented in Figure 3 by curve 1 for the autarky situation, and by curve 2 for the trading situation. Through trading with the outside, the $CC_{reality}$ of a population is enhanced. The result can be regarded as the sum of $CC_{autarky}$ and a partial dependence on available trade (Van den Bergh and Verbruggen 1999). The $CC_{autarky}$ for curve 1 can be calculated as:

$$CC_{autarky} = \frac{BC}{ef_a} \quad (13)$$

where BC is the total available biological capacity of a given region or country in a global ha, and ef_a is its EF per capita in global ha. In other words, trading is allowed, but only up to the point where the sum of (hypothetical) domestic and foreign land use equals available productive

Figure 3. Population development and ecological carrying capacity under three priority scenarios of autarky, trade and GDP.

land in the region. $CC_{reality}$ is the actual population carrying capacity of a given region. CC_{trade} is trade-sustaining population carrying capacity. The $CC_{reality}$ of curve 2 can be calculated as:

$$CC_{reality} = CC_{trade} + CC_{autarky}. \quad (14)$$

Since trading occurs between all regions, the purchase power can support the related exchanges of goods, and the consumption of goods indicates the definite level of EF. The potential population a region can support with the current life style can be defined as CC_{gdp} in curve 3, and CC_{gdp} can be obtained by integrating Equation (9) as:

$$CC_{gdp} = (1 - k) \text{ GDP} \left(\frac{T_{fr}}{ef_a} \right) \quad (15)$$

$$CC_{max} = \frac{EF_{mex}}{ef_a} = (1 - k) \text{ GDP} \left(\frac{T_{fm}}{ef_a} \right) \quad (16)$$

where T_{fr} refers to the EF/US\$1000 for a region or country, with a unit of global ha/k\$, the variable T_{fm} and constant k have the same meaning as in Equation (9), and ef_a is the

average amount of EF per capita for the studied region. The numerators of Equations (15) and (16) refer to a country or region's GDP that can be exchanged for the quantity of global hectares using the same money. If $CC_{gdp} > CC_{reality}$, the economy can support the population, and the area is sustainable. The population space of a region or country can be determined as:

$$\text{Population space} = CC_{gdp} - CC_{reality}. \quad (17)$$

Usually, some of the population space is occupied by imported labour and tourists, so the local population space can be obtained by subtracting these two items.

Sources of data

The original data on Macao for this analysis are available from the Statistics and Census Service of Macao (<http://www.dsec.gov.mo>, DSEC 2005). Other sources of data are specified where the related analysis or calculation appears.

Results and discussion

Ecological footprint and bio-capacity in Macao

Macao is very small, and most of its food and water are imported from Mainland China. Based on the proposed formulae above, the per capita footprint of Macao from 1977 to 2004 was calculated (Tables 1 and 2). The per capita EF of Macao was 3.716 ha in 2004, while the existing bio-capacity per capita was only 0.012 ha (Table 3), a per capita ecological deficit of 3.704 ha. From 1977 to 2004; the EF in Macao increased to 3.81 ha in 1992, then decreased to 3.05 ha in 2001, and again increased to 3.72 ha in 2004. The major components of EF in Macao are fossil energy, arable and pasture land, of which fossil energy land has the largest EF. The ecological deficit in Macao reflects a shortage of natural resources; in 2004 the total EF was 1,729,179 ha, and total equivalent bio-capacity was only 6515 ha, i.e. the EF was 265.4 times the actual land area of Macao. Obviously, Macao is highly dependent on supporting material and energy flows from outside ecosystems through trading.

Table 1. Ecological footprint of Macao in 2004.

Demand (ha/capita)				Bio-capacity (ha/capita)			
Category of land	Area	Equiv. factor ^b	Equiv. area	Category of land	Area	Yield factor	Equiv. area.
Fossil energy	1.412	1.1	1.608	CO ₂ absorp.	0.000	1.86	0.000
Built-up area ^a	0.003	2.8	0.008	Built-up area	0.004	0.73	0.008
Arable	0.361	2.8	1.017	Arable	<0.000	0.73	<0.000
Pasture	0.908	0.5	0.491	Pasture	<0.000	20.80	0.003
Forest	0.018	1.1	0.021	Forest	0.001	1.86	0.002
Marine area	1.555	0.2	0.338	Marine area	0.001	1.00	<0.001
Freshwater		0.2	0.233	freshwater	0.000		0.000
				Total existing	0.006		0.014
Total used	4.257		3.716	Total avail.	Less 12% for biodiversity ^c		0.012

^aFor the build-up area, the average world value was adopted for calculation.

^bSources of parameters of equivalence factors: Wackernagel et al. EFs of nations, commissioned by the Earth Council for the Rio+5 Forum, International Council for Local Environmental Initiatives, Toronto, 1997.

^cThis percentage was suggested by the EF approach of Wackernagel and Rees (1996) and Wackernagel et al. (2005).

Table 2. Ecological footprint components for Macao from 1977 to 2004.

Year	Fossil energy	Built-up area	Arable	Pasture	Forest	Marine area	Freshwater	Total footprint
1977	0.380	0.009	0.618	0.409	0.084	0.338	0.109	1.948
1980	0.568	0.009	0.741	0.511	0.094	0.338	0.147	2.408
1983	0.644	0.008	0.929	0.513	0.079	0.338	0.122	2.633
1986	0.740	0.007	0.955	0.506	0.035	0.338	0.153	2.734
1989	1.254	0.007	0.954	0.488	0.093	0.338	0.194	3.328
1992	1.654	0.006	1.033	0.465	0.097	0.338	0.215	3.808
1995	1.095	0.007	1.082	0.445	0.053	0.338	0.228	3.247
1998	1.102	0.007	0.980	0.436	0.035	0.338	0.231	3.129
2001	1.136	0.008	0.896	0.433	0.014	0.338	0.226	3.051
2004	1.608	0.008	1.017	0.491	0.021	0.338	0.233	3.716

Table 3. Biologically productive area available in Macao in 2004.

Land category	Area (ha)	% land area	Equiv. area of bio-capacity ^c (ha) ^a
Arable	5	0.2	<0.001
Forest	534	19.4	0.002
Pasture	140	5.1	0.003
Marine area	330	12.0	<0.001
Built-up area	1741	63.3	0.008
Total	2750	100.00	0.014 ^b

^aPer capita equivalent area of bio-capacity is actual area of that type of land in Macao multiplied by its equivalence factor and yield factor.

^bThe 12% area for biodiversity was not excluded.

^cPopulation of Macao in 2004 was 465,330.

Components of ecological footprint in Macao

Consumption of biological resources

Macao consumes many types of biological resource, mainly plant or animal-based food products, forestry products, and non-food products (Table 4). For each category of product, there are sub-categories that can be further identified. Most biological products were from outside Macao, and import of products is usually larger than export. Consumption of biological products mainly depends on trading with Mainland China. Food was the largest component of the per capita EF of biological resources in Macao in 2004, followed by plant and animal fibres and timber products (Table 4).

Consumption of energy

Energy in Macao is mainly obtained from coal and petroleum products. All the energy was imported from outside, and the biggest footprint per capita for energy in 2004 was heavy oil, followed by diesel; the footprint for coal was a very small proportion of the total EF per capita for the city (Table 5).

Consumption of manufactured or processed products

Manufactured or processed goods in Macao are very diverse, including water, beverages, unprocessed materials, chemicals, processed industrial materials, industrial products, miscellaneous manufactured goods and other

products. Using formula (5), energy conversion constants and energy intensity (Table 6), the main components of EF were beverages, minerals, organic chemicals, textiles, iron and steel, metal products, industrial machinery, general industrial products, vehicles and miscellaneous manufactured goods. In the total EF of fossil energy land, manufactured or processed products accounted for 35.5%.

EF/money ratio and EF trade balance

The EF approach is a biophysical analysis and needs to be integrated with economic analysis. So an indicator of EF per US\$1000 was introduced to analyse relationships between EF changes and economic growth in Macao, and was further used to assess ecological carrying capacity in Macao from 1977 to 2004 (Table 7). From 1977 to 2004, GDP increased quickly, being faster than population growth, the EF per capita and GDP per capita increased from 1977 to 1992, then declined until 2001, and rose again in 2004. Dividing GDP by the total EF of Macao, the economic output of per unit EF was calculated to assess ecological economic efficiency. GDP per unit EF increased from 1977 to 2004, indicating that the economic system of Macao had become more efficient in terms of resource use and tourism services. But EF/US\$1000 decreased in this period, meaning that the city can now buy less material goods or services with the same money (Table 7).

According to Table 8 and results of other researchers (Warren-Rhodes and Koenig 2001; Redefining Progress 2002; Liu and Peng 2004), Macao's economy was highly efficient, and its EF/BC was high, the higher the ratio, the bigger its ecological loading. A country or region with a high population density faces high ecological pressure, which is indicated by the EF/BC (van den Bergh and Verbruggen 1999). Cities or regions like Hong Kong, Macao and Singapore, have a high population density, insufficient ecological carrying capacity for the city's long-term consumption, and high ecological pressure. Macao faces the highest ecological pressure with the biggest EF/BC of 308.4. Macao had the lowest EF/US\$1000 among the above areas because it imports most products from China, and only has a few products or embodied EF (largely embodied EF of fossil fuels and freshwater) by trading with Mainland China or other regions for the same money

Table 4. Ecological footprint components of biological resources in Macao in 2004.

Category	Global average productivity (kg/ha)	Total production (t)	Import (t)	Export (t)	Total consumption (t)	Footprint per capita (ha/cap)	Footprint category
1. Food			250,233.00	4838.00	245,395.00		
Meat	74		40,705.00	400.00	40,305.00		
Beef, Goat	32.83		4511.90	60.64	4451.26	0.2914	Pasture
Other	457.33		36,193.14	339.36	35,853.80	0.1685	Arable
Dairy			29,580.15	2164.36	27,415.80	0.1173	Pasture
Milk	502.12		15,615.15	83.16	15,532.00		
Cheese	502.12		821.85	0.84	821.01		
Oil	502.12		272.50	82.00	190.50		
Fish	28.93	1624.00	19,172.00	662.00	45.00	1.5553	Marine area
Crops	2744		45,789.36	438.64	45,350.70	0.0355	Arable
Wheat			1373.68	8.77	1364.91		
Cereals			44,415.68	429.87	43,985.80		
Animal feed	2744		4366.00	152.00	4214.00	0.0033	Arable
Fruit and vegetables	18,000		71,067.60	195.80	70,871.80	0.0085	Arable
Vegetables			46,904.62	48.95	46,855.70		
Fruit			24,162.98	146.85	24,016.10		
Roots, Tubers	12,607		3740.40	24.20	3716.20	0.0006	Arable
Pulses	852		4230.10	93.96	4136.14	0.0104	Arable
Coffee, Tea	566		1424.80	259.80	1165.00	0.0044	Arable
Cocoa	454		1315.20	173.20	1142.00	0.0054	Arable
Sugar	4892.54		8041.00	114.00	7927.00	0.0035	Arable
Oil seeds	1856		20,801.75	160.00	20,641.80	0.0239	Arable
2. Timber	1.99 ^a		72,373.05	55,554.64	16,818.40	0.0182	Forest
Woods (m ³)	Waste factors	6680.17	188.80	6491.37			
Fuelwoods (m ³)	0.53		1090.64	141.60	949.04		
Raw timber (m ³)	1				0.00		
Sawed wood (m ³)	1.3		5862.19	2029.60	3832.59		
Sawn wood (m ³)	1.95		20,676.00	4335.00	16,341.00		
Pulp (t)	1.98		1.00	21,611.00	1.00		
Paper (t)	0.53		32,411.00	2660.00	29,751.00		
3. Other							
Tobacco	1548		5116.00	1327.60	3788.40	0.0053	Arable
Cotton	1000		2617.00	1567.60	1049.40	0.0292	Arable
Jute	1500		2322.40	861.96	1460.44	0.0018	Arable
Rubber	1000		1751.00	35.60	1715.40	0.0037	Arable
Wool	15		1112.10	722.44	389.66	0.4749	Pasture
Hides	73.98		1690.50	854.80	835.70	0.0243	Pasture
Trade balance of textiles						0.0566	Arable

^aProductivity of timber in m³/ha.

Table 5. Ecological footprint components of energy consumption in Macao in 2004.

Categories of energy	ECC ^a (GJ/ha)	Per capita energy consumption (GJ/cap)	Import (kg)	Export (kg)	Total energy consumption (t)	Per capita EF (ha/cap)
Coal	55	0.0002	5	0	5	4.09E-06
LPG	71	3.1897	29,567	0	29,567	0.0449
Gasoline	93	4.6361	50,027	0	50,027	0.0499
Kerosene	93	2.6492	28,587	0	28,587	0.0285
Diesel	93	15.0850	164,373	0	164,373	0.1622
Heavy oil	93	42.4391	471,680	0	471,680	0.4563
Added heavy oil ^b	93	3.8978	43,321	0	43,321	0.0419
Added diesel ^b	93	0.0953	1039	0	1039	0.001
Total ^c						0.7847

^aECC denotes energy conversion constants.^bIn 2004, Macao imported 151 kwh of electricity from Mainland China; if this amount of electricity is produced in Macao, it uses more heavy oil and diesel, so this additional consumption of fuel was included in the table.^cPer capita EF of energy consumption is in a unit of fossil energy land.

Table 6. Ecological footprint components of manufactured or processed products for Macao in 2004.

Category	Energy intensity (Gj/t)	Import (t)	Export (t)	Energy embodied in import (Gj)	EF per capita (ha)	Land category (ha)
Water		53,392,119				
Beverages	10	92,536.67	1712	0.9082	0.0275	Fossil
Crude materials						
Pulp and waste paper	5			0	0.0000	
Minerals	1.5	1,221,686	49,155	1.7588	0.0532	Fossil
Chemicals		70,663	10,728			
Organic chemicals	40	54,121	5718	1.9361	0.0586	Fossil
Dyes, tanning	20	4320	1008	0.0662	0.0020	Fossil
Pigments, paint	3888	604.8				
Medicinal and pharmaceutical products	20	2467	311	0.0431	0.0013	Fossil
Plastics	50	9755	3691	0.3032	0.0092	Fossil
Processed industrial materials		288,317	89,571			
Rubber products	35	3973	297	0.1287	0.0039	Fossil
Textiles	20	104,635	60,092	0.8909	0.0270	Arable
Iron and steel	30	137,343	1803	4.0662	0.1231	Fossil
Metal products	60	42,366	27,379	0.8992	0.0272	Fossil
Industrial products		38,585	6668			
Power generating	140	3311	362	0.41286	0.0125	Fossil
Industrial machinery	100	10,337	1857	0.848	0.0257	Fossil
Metal processing machinery	100	550	289	0.0261	0.0008	Fossil
General industrial	100	16,240	2752	1.3488	0.0408	Fossil
Office accessories	140	5288	1489	0.5319	0.0161	Fossil
Telecoms	140	4740	656	0.5718	0.0173	Fossil
Electric machinery	100	8870	3182	0.5688	0.0172	Fossil
Road vehicles	140	13,475	734	1.7837	0.0540	Fossil
Miscellaneous manuf. goods		180,698	137,821			
Clothing and accessories	20	108,134	99,988	0.1629	0.0049	Arable
Precision instruments	100	1913	724	0.1189	0.0036	Fossil
Misc. manuf.	100	70,651	37,109	3.3542	0.1015	Fossil
Other						
Transacted goods	5	3	0	0	0.0000	Fossil
Jewelry	150	0	0	0	0.0000	Fossil
Total				44.5458	0.5708	Fossil

Table 7. The EF/US\$1000 ratio in Macao from 1977 to 2004.

Category	1977	1980	1983	1986	1989	1992	1995	1998	2001	2004
Population	231,709	241,950	276,911	301,480	330,410	377,983	415,030	425,190	436,686	465,333
GDP (Million \$)	539	857	1281	1671	2955	4893	6559	6186	6229	10,306
EF/US\$1000	0.84	0.68	0.57	0.49	0.37	0.29	0.21	0.22	0.21	0.17
US\$1000/EF	1.20	1.47	1.76	2.03	2.69	3.40	4.87	4.65	4.68	5.96

Note: US\$1000/EF denotes economic output in US\$1000 per unit EF for Macao.

Table 8. Comparisons of EFs and ecological economic efficiencies between Macao, China and the world.

Country	Area (ha)	GDP (Billion US\$)	BC (ha/cap)	EF (ha/cap)	EF/GDP (ha/k\$ ^c)	GDP/EF (k\$/ha ^c)	EF/BC	BC _{trade} (ha)	Ecological Deficit (ha)
World (1999) ^a	5.10E + 10	43,600.6	1.9	2.3	0.32	3.08	1.2		2.46E + 09
China (2001) ^b	9.60E + 08	1400.4	1.05	1.47	1.34	0.74	1.4	3.64E + 08	5.38E + 08
Macao (2004)	2.75E + 03	10.3	0.01	3.72	0.17	5.96	308.4	2.68E+06	1.72E + 06

BC is bio-capacity per capita.

^aRedefining Progress2002.

^bLiu Y.H. et al. 2004.

^ck\$ = US\$1000.

Figure 4. Comparison of 1000\$/EF ratio of different countries or regions in 2002.

Note: "1000\$/EF to Macao" denotes the ratio of Macao's value of 1000\$/EF to that country or region, for Macao, this value of the ratio is unity.

without payment for ecosystem damage. But Macao had the highest US\$1000/EF, i.e. the highest ecological economic efficiency, while China has the lowest ecological economic efficiency and the lowest US\$1000/EF (Figure 4).

EF related population carrying capacity

According to Equations (13) and (14), the population carrying capacity for Macao is 2951 people, the remaining 462,382 people are sustained by net import of bio-capacity. If all Macao revenue was used to import bio-capacity, a maximum of 876,000 people (including labour and tourists) could be sustained. According to Equation (17), in 2004, there were 103,507 tourists per day, so the local population space = $CC_{gdp} - CC_{reality} - \text{labor} - \text{population equivalent of tourists} = 876,000 - 465,333 - 39,028 - 103,507 = 268,132$. Actually, if other demands for transportation, houses, education, hospital and social welfare, etc. are considered, the theoretical maximum population can never be reached.

Conclusions

Although EF has several inherent limitations, such as limited inclusion of land use, and some assumptions of equivalence factors for calculation, it can approximate the actual impacts of human demand on natural ecosystems. EF analysis, together with other economic analyses, presents an approach for analysing sustainable population and identifying some priority points relating to 'strong' and 'weak' sustainability and unsustainability. If the required area exceeds the available biological capacity, overuse of natural resources ensues, thereby violating the principle of strong sustainability. Ecological overshoot identifies the need for inter-regional or international trade of natural capital, which requires substitutable man-made capital to maintain the criterion of weak sustainability. To make EF analysis more operational and reasonable, trading of embodied EF between regions or countries on a global scale needs to be considered in its calculating framework. EF analysis can be used to clarify relationships between ecological carrying capacity and inter-regional or international trade. Indeed,

in general the smaller a region, the more it trades with other regions. Through economic exchanges of goods or services, the traded EF surplus for a country, region or city can compensate for the shortage of local ecological resources and allow it to expand its population carrying capacity ($CC_{gdp} > CC_{reality}$) so as to sustain its sustainable development. Integrating biophysical flows with economic indicators in our study makes EF analysis more useful to establish a unified analysis framework for assessing the sustainability of populations by inter-regional or international trading.

Our calculations were based on the required areas of biophysical flows from various consumption analyses, as suggested by Wackernagel and Rees (1996) and Wackernagel et al. (2005), using original data from the government of Macao. Our research has found a measure to indicate whether a country, regional or city can sustain its population if available trade can balance supply and demand of the embodied EF among countries, regions or cities. For Macao, a consumption-type city with almost all the embodied EF imported from the outside, our results can be used to help it to reasonably design development plans and balance its shortage of resources through international or regional trade.

Our research is preliminary, and further research is necessary for some important issues, such as improvements in calculating parameters and increased data for EF analysis, analysis of influential factors in Macao's EF trade with other regions or countries, and improvement to the calculation method for population carrying capacity, such as CC_{trade} and CC_{gdp} , to make more accurate estimates. Population carrying capacity is an important issue for planning and management of city or regional sustainable development. Our research has presented an operational approach for its estimate, which will help cities or regions to adjust their consumption towards higher sustainability.

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