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Emergy synthesis of tourism-based urban ecosystem

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Abstract

Macao is a tourist city with a dense population, but is short on natural resources. Almost all of the life-support resources of the city depend on imports from outside. During the past 20 years, Macao has experienced an economic boom accompanied by rapid social development. The tourism industry (including gambling, hotel accommodation, restaurant dining, and shows) have become the city's main economic activity since 1991. This paper uses emergy flow analysis to investigate and characterize the urban evolution and city development that have occurred in Macao from 1983 to 2003. Macao's tourism industry has existed almost from the establishment of the city, with the legalization of gambling in Macao occurring in 1850. Tourism has become the biggest industry in Macao, contributing more than half of the city's revenues since 1995. The emergy flow related to tourism was tracked and analyzed to measure its contribution to Macao. In addition, we used statistical analysis to divide the various emergy-based indicators into three categories: positive, negative, and insensitive indicators.

Keywords: Emergy synthesis; Emergy-based indices; Net emergy; Net emergy ratio; Tourism; Gambling; Macao

1. Introduction

Since the concept of "embodied energy" (emergy) was first introduced in the 1980s, emergy has become of increasing interest to researchers. Emergy analysis considers all systems to be networks of energy flows and determines the emergy value of the systems involved through a synthetic approach. "Emergy is a universal measure of real wealth of the work of nature and society made on a common basis" (Odum and Odum, 2001). Synthesis of emergy flows provides an energy basis for quantification or valuation of the goods and services embodied in ecosystems. Since the early 1980s, the emergy framework has been widely used to analyze systems as diverse as ecosystems, industries, and economies. The relevant indices and ratios based on emergy flows can be used to evaluate the behavior of ecological economic systems (Brown and Ulgiati, 1997).

Emergy synthesis is necessary to obtain not only a reliable evaluation of a system's or region's performance over a period of time, but also a comparison of the system's or region's sustainability compared with other systems or regions. Time-series analyses have proved to be very useful in understanding the dynamic trends in sustainability (Huang and Odum, 1996; Cialani et al., 2005; Hagström and Nilsson, 2005) because this approach can be applied to systems ranging in size from cities to countries. Studies using this approach have highlighted the importance of regularly updating regional and national statistics, since the time series can reveal variation in the ecological parameters of economic systems.

For the purposes of this paper, we have defined tourism as the activities of persons traveling to places outside their usual environment for leisure, business, and other purposes not related to receiving monetary remuneration from the place being visited. The World Tourist Organization (WTO) defined sustainable tourism development as "a form of development, provision of amenities, or tourist activity that emphasizes respect for and long-term preservation of natural, cultural, and social resources and

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makes a positive and equitable contribution to the economic development and fulfillment of people living, working, or staying in these areas".

Since the early 1980s, the framework of emergy synthesis has been used to analyze tourism (Abel, 2000, 2003; Brown and Ulgiati, 2001). Brown and Ulgiati (2001) have studied tourism resorts in Mexico and Papua New Guinea, and proposed that sustainable development was related to the net emergy benefits, and that sustainability was likely to result from a positive emergy balance. This paper applies the approach of emergy synthesis to investigate Macao's emergy changes from 1983 to 2003 from economic and environmental perspectives.

2. Environmental and economic characteristics of Macao

Located on the west coast of the Pearl River estuary in southeastern China, Macao is characterized by more than 400 years of cultural mixture between the Western world and China, and has a population of 465,333. Macao lies between longitudes 111°31′33″E and 111°35′43″E, and between latitudes 22°06′39″N and 22°13′06″N. Macao consists of the Macao Peninsula, Taipa Island, Coloane Island and some reclaimed land (Fig. 1). In total, it covers an area of 27.5 km^2 (The Statistics and Census Service, 2004).

Colonized by the Portuguese in the 16th century, Macao was the first European settlement in the Far East. Pursuant to an agreement signed by China and Portugal on 13 April 1987, Macao became the Macao special administrative region (SAR) of China on 20 December 1999. Because of Macao's architectural heritage, the city has officially been listed as a World Cultural Heritage site since 2005.

Tourism (including gambling-related activities), manufacturing, finances and insurance, and construction and real estate development were thought of the four pillars of Macao's economy since 1980. Since then, Macao has become a consumer economy, particularly after both the agriculture and the fishery sectors began to decline in 1990. Moreover, the manufacturing sector has found it increasingly difficult to compete with factories in Mainland China, leading to a migration of factories to southern China. Although Macao's daily necessities for life (water, food, fuel, raw materials, and goods) depend upon imports, the economy has maintained robust growth and sustained prosperity based on the gambling and tourism industry (henceforth, the "tourism" industry). In 2003, Macao's GDP reached MOP 63.37 billion, or about $10 billion at an exchange rate of 8.021 MOP per $. The booming tourism industry contributed taxes amounting to $1.9 billion from gambling (The Statistics and Census Service, 2004). By liberalizing the gambling industry, the government has also set in motion further tourism redevelopment. Two new casinos were opened under new foreign gambling licenses issued in 2004. In the future, it appears likely that Macao's economy will rely increasingly on tourism and trade-related services to sustain its growth.

3. Methodology

3.1. The emergy accounting method

Emergy synthesis was used to quantify both environmental and economic systems. The energy inputs from environmental sources (*R*, also referred to as the "renewable resource inputs") are tides, waves, and rain; the energy and materials imported from outside Macao (*F*) are water, raw materials for industry, minerals for infrastructure construction and the reclamation of land, food, fuel, a small input of electricity, goods, and labor. The outflow of energy (*Y*) comprises products and tourism service exports. The waste emergy (*W*) involves urban rubbish that is incinerated, municipal wastewater discharged after treatment, and gaseous emissions of pollution into the ambient air.

Within this context, emergy is defined as all the energies that are consumed to produce a product, with each of these

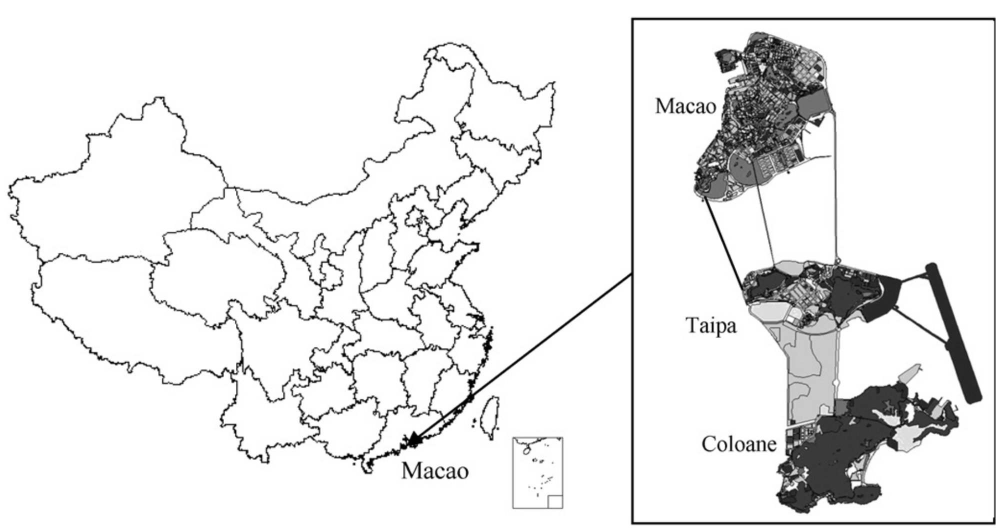

Fig. 1. The location of Macao.

energies expressed in standard energy units. Transformity is defined as the quantity of one type of emergy required to generate a unit of energy of another type, and is expressed in solar energy joules (sej) per joule. Thus, the transformity of a product (τ) equals its emergy divided by the available energy, and the emergy can be express as

$$M = \tau E, \tag{1}$$

where M is the product's emergy (sej) and E is the available energy (J). The emergy of economic inputs measured in monetary terms is determined by

$$M = (\text{Emergy}/\$)C, \tag{2}$$

where C represents a particular economic input (usually in \$), Emergy is the total emergy used by the region or nation whose emergy is being analyzed, and *\$* is the gross domestic product of the region or nation. The emergy used by tourists (M_t, representing goods and services) can be considered as an emergy export (Abel, 2000). M_t can be calculated using the following equations:

$$R_t = Tdr/(Tdr + 365P), \tag{3}$$

where R_t is the ratio of M_t to emergy used (U), T is the annual number of tourists, d is the average duration of their stay within the study area, P is the population of Macao, and r is the tourist's consumption factor (i.e., the ratio of emergy consumption by a tourist to emergy consumption by a native of Macao). As a result:

$$M_t = R_t U. \tag{4}$$

Based on an investigation of the consumption behavior and on other tourist data (The Statistics and Census Service, 2004; the 2003 data was used), r was estimated based on the following Figures (2003 data) compared to the values for a local citizen: 1.89 times the water, 2.14 times the electricity, 3.3 times the shopping commodity, 1.3 times the food, 1.5 times the transportation, and 1 times all other categories. Multiplying each of these items by its percentage of the total emergy used by the Macao area produces a weighted value for r:

$$1.89 \times 0.84\% + 2.14 \times 6.71\% + 3.3 \times 32.5\% \\ + 1.3 \times 15.41\% + 1.5 \times 5.49\% + 1 \times 39.05\%.$$

Using the same weighting method, we obtained r values of 2.0 in 2000, and of 1.77 in 1997. We have chosen the average value of r for these three years (1.9) for all subsequent calculations. This means that a tourist consumes 1.9 times the emergy of a local citizen, averaged over all inputs.

We defined the following additional emergy-based indicators for use in our analysis:

Imports (F): The flow of emergy imported in the form of goods and services from outside the region, including fuels, minerals, raw materials, goods, and imported services.

Exports (Y): The flow of emergy exported in the form of goods and services to the outside market, including exported productions (B) and tourism (M_t).

Emergy exchange ratio (EER): The ratio of emergy exchanged in a trade or purchase (i.e., the ratio of emergy received to emergy given).

Environmental loading ratio (ELR $= (N+F)/R$): The ratio of nonrenewable emergy (N) and imported emergy (F) to renewable emergy (R).

Emergy investment ratio (EIR): It equals the imported emergy (F) divided by the indigenous emergy ($R+N$).

Emergy yield ratio (EYR): The ratio of the emergy yield from a process to the emergy costs. The ratio is a measure of how much a process will contribute to the economy (Brown and Ulgiati, 2001).

Emergy sustainability index (ESI): The ratio of EYR to ELR.

Net emergy: The surplus emergy or emergy deficit of the system or region as a result of the exchange process and the nonrenewable emergy exploited during the year under investigation (Ulgiati et al., 1995; Lei et al., 2006), where net emergy $= R + F - Y$.

Net emergy ratio (NER): The ratio of net emergy to the emergy used (U).

3.2. Statistical correlation and regression methods

In this research, correlation method has been employed using version 13 of the SPSS software (SPSS Inc., Chicago, Il.). Correlation coefficients were calculated for linear relationships between pairs of variables (James, 2002). We used the Pearson bivariate correlation method to measure the statistical relationship between each pair of emergy-based indices.

4. Results and discussion of the time series for emergy change

4.1. Emergy synthesis for the Macao ecological–economic system in 2003

Urban ecosystems consist of a large number of people living in close proximity. They serve as centers for both residential and commercial activities. The existence of a city or town, and the maintenance of its internal structures, depends on the inflow and outflow of goods and services required to sustain these activities (Huang and Chen, 2005). Urban ecosystems exhibit the same basic kinds of interactions exhibited by other ecosystems. Most importantly, from the perspective of the living species contained by the urban ecosystem, none of these ecosystems are ecologically self-contained or self-sufficient; that is, cities are all sustained by biophysical processes that occur mainly outside the city. Highly populated cities such as Macao could not exist without the support of a larger surrounding ecosystem (Huang and Odum, 1996). We performed an emergy analysis for Macao to ensure that the importance of these external inputs was recognized in our analysis, and created a diagram (Fig. 2a) that depicts the environmental resources provided by the natural area surrounding

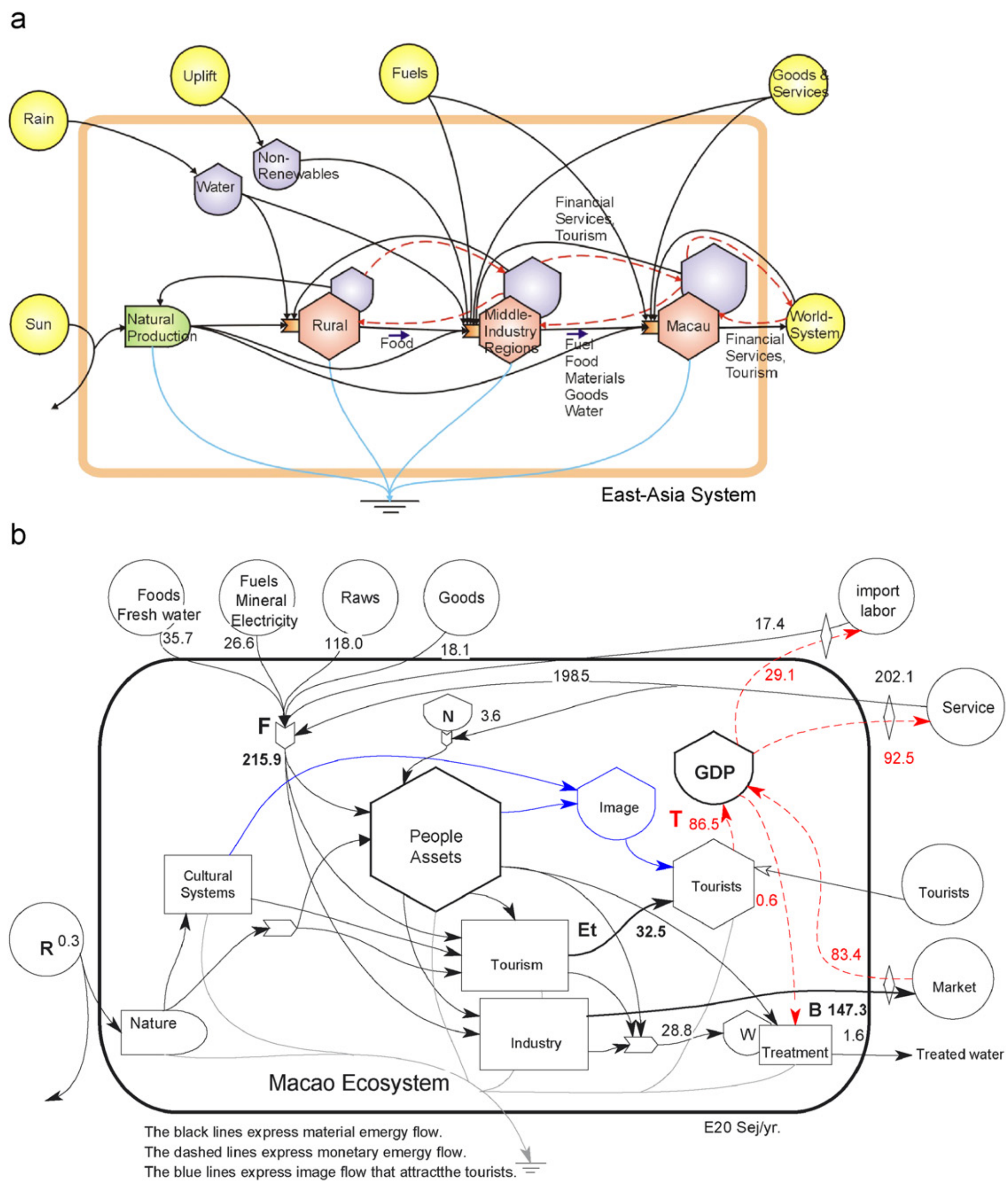

Fig. 2. (a) A concise diagram of flows of energy and materials within and between Macao and its supporting systems (figure drawn by Abel of Tzu Chi University, Taiwan). (b) A concise emergy diagram for Macao's ecosystem in 2003 (values are $\times 10^{20}$ sej).

Macao. These resources are concentrated in rural areas, where solar energy is stored in biological materials, accumulated, used to support moderately urbanized regions, and finally, transferred to the high-density city of Macao, which exchanges emergy with the surrounding ecosystem (Huang and Odum, 1996). Materials and energy flow inwards from the rural area to the suburban areas, and then to the urban area, resulting in a concentration of the energy in the city. In the case of our study area, Macao's life support energy and materials are mostly provided by the surrounding areas of Mainland China.

Most of the data used in this paper were provided by the Statistics and Census Service of Macao (The Statistics and Census Service, 2004), the Meteorological and Geophysical Bureau of Macao (SMG), the Office for Infrastructure Development of Macao (GDI), the Environment Council of Macao (2003), and the Gaming Inspection and Coordination Bureau of Macao (DICJ). Table 1 summarizes material flows (imports and exports) for Macao in 2003. Imports totaled about 56.7×10^9 kg of fresh water, versus 2.61×10^9 kg of other goods and raw materials. This contrasts with exports of 48.8×10^9 kg of sewage discharged and 0.42×10^9 kg of products exported to regions outside Macao. We found that the production of exports amounted to only 0.7% of the imported materials (weight basis). Fresh water was the main imported material, and

Table 1
Material flows for Macao in 2003

No. Item	Import ($\times 10^9$ kg)	% of total imports	Export ($\times 10^9$ kg)	% of total exports	Wastes (treatment)	Quantity of wastes ($\times 10^9$ kg)
1. Water	56.67	95.7	0	0.0	Sewage (discharged)	48.8
2. Food	0.01	0.0	0.01	1.6		
3. Fuels	0.61	1.0	0.0009	0.0	Solid wastes (incinerating)	0.25
4. Minerals	1.15	1.9	0.09	21.6		
5. Raw and processed materials	0.53	0.9	0.26	61.3		
6. Goods	0.31	0.5	0.06	15.5		
Total	59.28	100.0	0.42	100.0		

Table 2
Annual emergy flow for renewable and nonrenewable resources for Macao in 2003

No. Item	Raw units (J, g)	Transformity (sej/raw unit)	Published value for transformity	Emergy ($\times 10^{16}$ sej)	Emdollars ($\times 10^5$ em$)
Renewable					
1. Sunlight	1.15×10^{17}	1	Odum (1996)	11.48	0.41
2. Wind, kinetic	9.97×10^{13}	623	Odum (1996)	6.21	0.22
3. Rain, chemical	2.01×10^{14}	18199	Odum (1996)	365.70	13.15
4. Rain, geopotential	3.99×10^{13}	8888	Odum (1996)	35.43	1.27
5. Waves	8.94×10^{14}	25889	Huang and Odum (1996)	2314.56	83.22
6. Earth cycle	3.96×10^{13}	29000	Odum (1996)	114.79	4.13
Total: (3+5+6)	1.15×10^{15}		–	2699.99	97.07
Nonrenewable					
7. Marble	3.60×10^{11}	1.00×109	Odum (1996)	36,000	1294.31
8. Topsoil loss	1.90×10^{9}	6.25×104	Odum (1996)	0.01	0.00
Total: (7+8)	3.62×10^{11}	1.00×109	–	36,000	1294.31

amounted to about 95.6% of the total imported material. Raw and processed materials were the main export, and amounted to about 61.3% of the total exports. About 98.4% of the imported material came from China, whereas 32.3% of products were exported to China. The imported electricity imported from China totaled 193 GWh in 2003.

Fig. 2b is a concise emergy flow diagram for Macao's internal and external environment and economy. Table 2 summarizes the renewable (R) and indigenous nonrenewable resources (N), Table 3 summarizes the emergy trade exchange (imports versus exports), and Table 4 summarizes the emergy flows for Macao in 2003. Fig. 2b shows imports of 17.4×10^{20} sej (labor and services), of 215.9×10^{20} sej purchased emergy (F), and of 86.5×10^{20} sej of tourist payments for their consumption flowing into Macao to support the system's metabolism.

In 2003, the imported emergy (F) equaled 98.2% of the total emergy used (U). Inexpensive raw materials usually carry plentiful emergy, thus the emergy/$ for China was 4.94×10^{12} sej/$ in 2003 (Zhao, 2001), versus only 2.78×10^{12} sej/$ for Macao. Thus, when Macao exchanges goods with China, emergy assets flow into Macao. Analysis of other development projects (Ulgiati et al., 1995) suggests that one of the main driving forces behind international trade is the fact that developed countries benefit greatly from an unequal emergy exchange with developing countries when they exchange goods with the developing region. Unequal emergy exchange related to the primary materials provided by different regions will lead to an emergy surplus when spending the same amount of money (Odum, 1996).

The EER represents the ratio of emergy exchanged in a trade or purchase (i.e., what is received divided by what is given), and is always expressed relative to one or the other trading partners to indicate the relative trade advantage of one partner over the other. According to Odum (1996), an EER value of more than 1 means that the received emergy exceeds the emergy that is given in exchange. In the present study, we analyzed all the EERs for the process of emergy exchange with the external system that surrounds Macao (Table 5). The results show a net positive EER, therefore the system will gain emergy and the current exchange processes will be advantageous to its survival and development. Macao benefited strongly from imported materials (EER = 2.21) and exchange with tourists (EER = 2.66). On the other hand, there were emergy losses in exported

Table 3
Emergy evaluation for imports and exports for Macao in 2003

Item	Weight (kg)	Raw data (J, g or $)	Transformity (sej/unit)	Published value for transformity	Emergy (10^{20} sej)	Emdollars (10^{7} em$)
Import material	5.93×10^{10}	3.33×10^{16}			198.5	528.9
Food	2.98×10^{8}	3.13×10^{15}	38 categories[a]	Summary of food	33.9	68.5
Fresh water	5.67×10^{10}	2.80×10^{14}	660,000	Lan et al. (2002)	1.8	3.7
Electricity[b]		6.44×10^{14}	159,000	Odum (1996)	1.0	2.1
Fuels	6.13×10^{8}	2.55×10^{16}	54,000	Odum et al. (2000)	13.7	82.5
Minerals	8.73×10^{8}	8.73×10^{11}	9 categories[c]	Mineral summary	11.9	24.0
Raw, materials	5.32×10^{8}	3.76×10^{15}	38 categories[d]	Summary of raw, materials	118.0	238.9
Goods	3.08×10^{8}	2.20×10^{11}	34 categories[e]	Summary of goods	18.1	109.1
Export production	4.19×10^{8}	2.54×10^{15}			114.8	412.7
Food	6.78×10^{6}	1.03×10^{14}	27 categories[f]	Summary of food	1.1	4.1
Fuels	8.99×10^{4}	2.23×10^{12}	54,000	Odum et al. (2000)	0.001	0.004
Cement	9.05×10^{7}	9.05×10^{10}	2.07×10^{9}	Brown and Buranakarn (2003)	1.7	6.4
Raw, materials	2.57×10^{8}	2.43×10^{15}	37 categories[g]	Summary of raw, materials	103.9	373.5
Goods	6.50×10^{7}	5.42×10^{10}	30 categories[h]	Summary of goods	8.0	28.8
Wastes	4.90×10^{10}	1.75×10^{15}			28.8	103.5
Solid waste (W_s)	2.49×10^{8}	1.51×10^{15}	1.80×10^{6}	Huang and Hsu (2003)	27.2	97.7
Sewage (W_l)	4.88×10^{10}	2.39×10^{14}	6.66×10^{5}	Huang and Hsu (2003)	1.6	5.7
Imported services		1.05×10^{9}	4.94×10^{12}	Zhao (2001)	17.4	35.2
Tourism (T_m)[i]		5.21×10^{9}	1.66×10^{12}	Brown	86.5	311.0
M_t[j]		R_t is 0.148	U is 2.2×10^{22}	Eqs. (3) and (4)	32.5	117.0

[a]Imported food was classified into 38 categories, and the results of the emergy calculation process are listed in supplementary Table S1.
[b]The purchased electricity purchased from China totaled 193 GWh; the equivalent energy was 6.44×10^{14} J.
[c,d,e,f,g,h]The imported and exported items were classified into different categories, and listed in supplementary tables S2–S7.
[i]The tourism emergy was calculated according to Eq. (3). The transformity of the world was obtained from Brown (University of Florida, Gainesville, personal communication, 2004).
[j]According to Eqs. (3) and (4), the consumer emergy of tourists $M_t = 0.148 \times 220 \times 10^{20} = 32.5 \times 10^{20}$ (sej).

$$R_t = \frac{11887876 \times 1.26 \times 1.9}{11887876 \times 1.26 \times 1.9 + 365 \times 448495} = 0.148.$$

products (EER = 0.57) and imported services (EER = 0.60). Macao's total EER equaled 1.28, which indicates that it would obtain a considerable emergy profit through its exchanges with the regions external to the system (Fig. 2b); the largest net emergy came from imported materials (108.5×10^{20} sej, equal to about 49.4% of U), followed by tourism exchange (54.0×10^{20} sej). By offering tourists a range of services and recreational opportunities, Macao profited by importing a large amount of money ($\$5.21 \times 10^{9}$). Table 5 shows that in 2003, Macao lost emergy in exported products (64×10^{20} sej), probably because many of Macao's factories have moved to Mainland China in the past 10 years. Macao also lost emergy in imported services (11.7×10^{20} sej).

4.2. Emergy and emergy-based indices for Macao

Fig. 3 presents the variations in various major components of the emergy flows for Macao from 1983 to 2003. Table 6 summarizes the emergy components and indicators used for the years under study. Imported fresh water, electricity, renewable resources, food, and imported services rose slowly as the population increased. Fossil fuel consumption increased every year (Fig. 3a), and the emergy of goods fluctuated in a narrow range (Fig. 3b) while nonrenewable resources declined from 1983 to 1990 (Fig. 3a) due to decreasing excavation of marble. Nonrenewable resources then remained at the same level until 2003. The emergy of raw materials was the largest imported item for Macao (Fig. 3b), and it increased as China's economy increased. The emergy of minerals was the second-largest imported item (Fig. 3b), especially during the period from 1985 to 1993, while the infrastructure and land reclamation were booming. The peak of Macao's development occurred in 1993, when mineral imports reached 5.09×10^{13} g, which was 5.28 times the 1992 value (9.65×10^{12} g) and 3.73 times the 1994 value (1.37×10^{12} g). In terms of the emergy value of these minerals, the value in 1993 was 1.6 times the 1990 value (43.8×10^{20} sej), and 6.0 times the 1995 value (10.1×10^{20} sej). At that time, the high quantity of mineral imports raised the imported emergy (F), so the amount of emergy used (U) and the imported emergy (F) were also the highest in that year (Fig. 3b, c).

From 1983 to 1993, the population and GDP increased (Fig. 3c). During the same period, U, imported emergy (F), exported emergy (Y), emergy density, and average

Table 4
Summary of emergy flows for Macao

Variable	Meaning and calculation method	Energy (J), money ($) or mass (g)	Solar emergy ($\times 10^{20}$ sej/year)	Emdollars ($\times 10^{9}$ em$)
R	Renewable resources (Table 2)	1.15×10^{15}	0.27	0.01
N	Nonrenewable resources (Table 2)	3.62×10^{11}	3.60	0.13
Fuel	Imported fuels and minerals (Table 3)	2.85×10^{16}	26.60	1.07
G	Imported goods (Table 3)	3.41×10^{15}	171.85	3.48
Imported services	Imported services (P_2I)	1.05×10^{9}	17.40	0.35
F	Imported emergy (fuel + G + P_2I)	3.20×10^{16}	198.46	5.29
U	Emergy used ($R + N + F$)	3.31×10^{16}	219.73	5.43
T_m	Tourism emergy income (Table 3)	5.21×10^{9}	86.50	3.11
M_t	Tourist emergy consumption (Table 3)		32.54	1.17
B	Export production (Table 3)	2.54×10^{15}	114.80	5.30
Y	Exported emergy ($B + T_m$)		147.34	6.47
W	Waste emergy (sewage, solid wastes)	1.75×10^{15}	28.78	3.11
ELE	Electricity emergy	6.77×10^{15}	10.83	0.39
GDP	Gross Domestic Product (US$)	7.90×10^{9}		
P_1	Emergy/$ ratio for Macao (sej/$)	2.78×10^{12}		
P_2	World emergy/$ ratio (sej/$)	1.66×10^{12}		
P_3	China emergy/$ ratio (sej/$)	4.94×10^{12}		

Table 5
The emergy exchange ratios (EER) for Macao in 2003

Item	Emergy received ($\times 10^{20}$ sej)	Emergy given in exchange ($\times 10^{20}$ sej)	EER	Surplus or deficit ($\times 10^{20}$ sej)	Notes
1 Imports of materials[a]	198.46	89.91	2.21	108.54	Imported money (US$): 3.23×10^{9}
2 Imports of services[b]	17.40	29.14	0.60	−11.74	Paid money (US$): 1.05×10^{9}
3 Exports of products[c]	83.35	147.34	0.57	−63.99	Exported money (US$): 3.00×10^{9}
4 Tourism emergy[d]	86.50	32.54	2.66	53.96	Exported services (US$): 5.21×10^{9}
Total for Macao[e]	385.72	300.53	1.28	85.19	

[a]Macao's import cost totaled 3.23×10^{9} US$. So the imports emergy = Import × (Macao emergy/$) = 89.9×10^{20} sej.
[b]Imports of services cost 1.05×10^{9} US$, Imports of services = $1.05 \times 10^{9} \times 1.66 \times 10^{12} = 17.4 \times 10^{20}$ sej.
[c]Imports of money into Macao totaled 3.00×10^{9} US$, thus received emergy = $3.00 \times 10^{9} \times 2.78 \times 10^{12} = 83.4 \times 10^{20}$ sej.
[d]According to Eqs. (3) and (4). R_t was 0.148, and M_t was 32.6×10^{20} sej, the exports of services = $5.21 \times 10^{9} \times 1.66 \times 10^{12} = 86.5 \times 10^{20}$ sej.
[e]Macao's EER was obtained by dividing the sum of received items (1, 2, 3, and 4) by the sum of given items. Renewable resources in the wastes category were not calculated in this total since wastes are not exchanged.

emergy all increased steadily (Table 6). After 1993, U, F, Y, and emergy density began to decrease slowly until 2000, then increased again (Fig. 3c, d). The increase in waste emergy indicated worsening environmental pressure (Fig. 3d, Table 6).

The ELR is an indicator of the pressure on the local ecosystem and can be considered a measure of the level of ecosystem stress due to production activities (Ulgiati and Brown, 1998). U and ELR fluctuated similarly in Macao. In the mid-1990s, GDP increased with increasing EIR and increasing ELR ratio. The emergy/$ ratio declined from 8.76×10^{12} sej/$ in 1983 to 2.78×10^{12} sej/$ in 2003, which indicates that during the past 20 years, the currency rose more quickly than U, something that also occurred in most other countries (Brown and Ulgiati, 1997). The average emergy used per capita in Macao was 3.55×10^{16} sej in 1983, and reached a maximum of 6.43×10^{16} sej in 1993. It then declined to 4.90×10^{16} sej in 2003. The ESI of Macao was very small (less than 0.0021) and declined from 1983 to 1993. In 1993 EYR remained stable while ELR reached its peak (915), so ESI decreased to its lowest value (0.0006), then increased until 2000 (0.0011) and declined again until 2003 (0.0008) (Fig. 3e, Table 6). An ESI < 1 appears to be indicative of an economy focused on consumer products or processes that reduce emergy sustainability, whereas an ESI > 1 appears to be indicative of products that have net contributions to the emergy sustainability of society. A low ESI (< 1) is considered to be indicative of highly developed consumer-oriented economies (Ulgiati and Brown, 1998). The ESI of Macao was just 0.0008 in 2003, versus a value of 0.013 for the US (calculated from data provided by Brown of the University of Florida, Gainesville, 2005, personal communication), 0.036 for Italy (Cialani et al., 2005), and 0.120 for Sweden (Hagström and Nilsson, 2005). This comparison clearly indicates that Macao has a highly developed consumer system compared with the

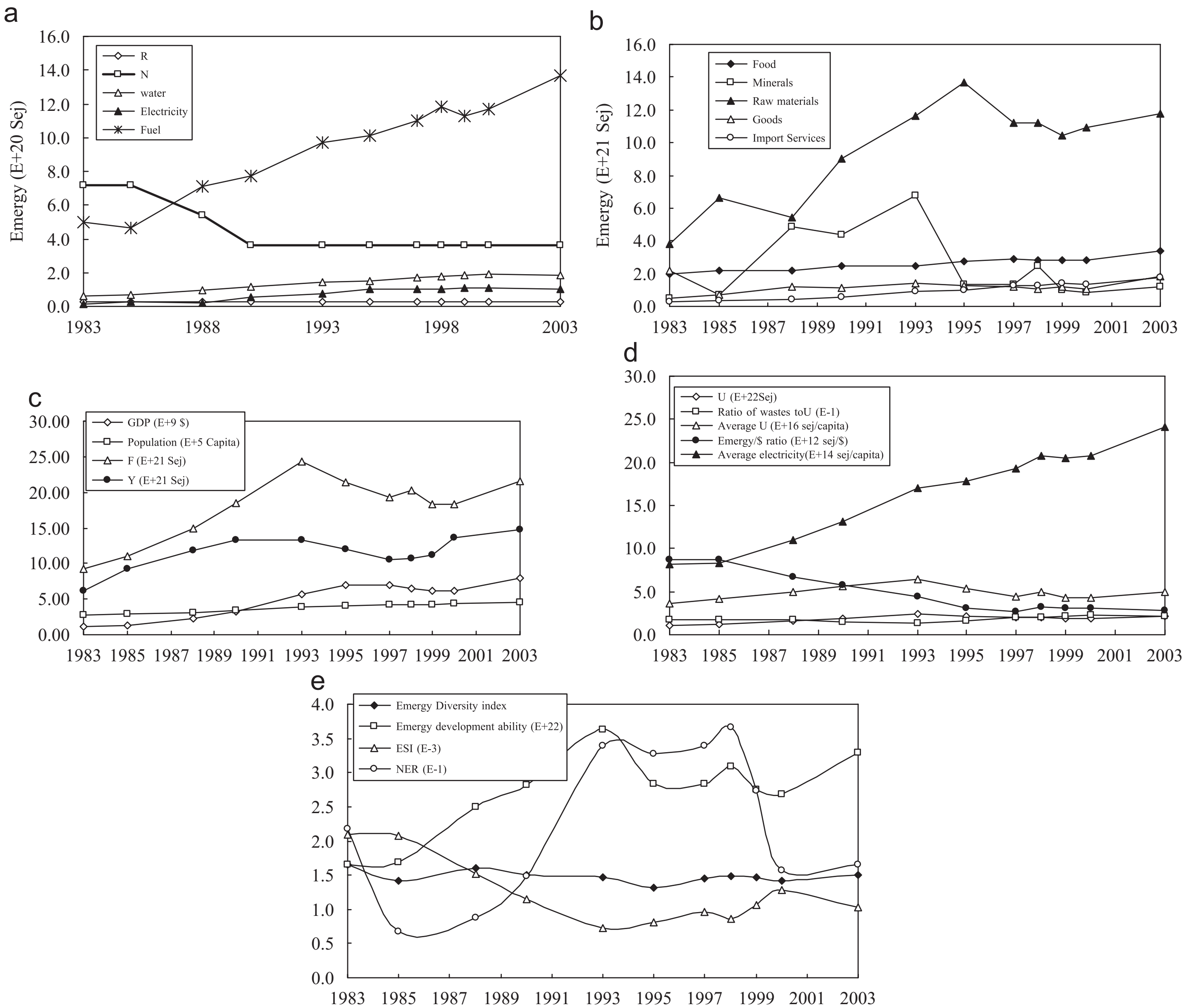

Fig. 3. Trends in major emergy components and related parameters from 1983 to 2003 in Macao. (a) *R*, *N*, water, electricity, and fuel. (b) Food, minerals, raw materials, goods, and imported services. (c) GDP, population, imported emergy, exports emergy. (d) *U*, ratio of the wastes, emergy/$ ratio, average electricity, and *U*. (e) ESI, NER, emergy diversity index, and emergy development ability.

other countries. The ESI declined as the economy grew, as measured by GDP growth during the study period (Fig. 3c, e).

Money is not real wealth, and real wealth includes food, minerals, fertile land, housing, information, arts, and other important factors (Ulgiati, 2004). Balancing the exchange of emergy between exports and imports may lead to more-sustainable development in the long run (Brown and Ulgiati, 2001) and may increase the real wealth of the citizens of Macao. The survival of a system depends on having a net emergy surplus (Ulgiati et al., 1995; Lei et al., 2006). The NER was 0.217 in 1983, dropped to 0.162 in 1985, increased until it reached its peak (0.447 in 1993), then decreased to 0.258 in 2000 before recovering to 0.313 in 2003. Fig. 3e presents the values of the emergy diversity index for Macao from 1983 to 2003. According to Shannon's equation (Xu et al., 2003):

$$\text{Emergy diversity index} = -\sum_{i}^{n} E_i \ln E_i, \tag{5}$$

where E_i is the emergy component of the emergy used. The emergy used (U) multiplied by the diversity index can be used to express the emergy development ability of a region (Xu et al., 2003). According to Ulanowicz (1986):

$$\text{Emergy development ability} = -\left(\sum_{i}^{n} E_i \ln E_i\right) U. \tag{6}$$

Table 6
Emergy components and emergy-based indices for Macao from 1983 to 2003

No	Item	Equation	1983	1985	1988	1990	1993	1995	1997	2000	2003
1	Renewable resources ($\times 10^{20}$ sej)	R	0.274	0.264	0.258	0.253	0.270	0.266	0.286	0.286	0.280
2	Nonrenewable resources ($\times 10^{20}$ sej)	N	7.20	7.20	5.40	3.60	3.60	3.60	3.60	3.60	3.60
3	Imported emergy ($\times 10^{20}$ sej)	F	92.98	111.04	149.07	184.88	243.15	213.44	192.65	183.72	215.86
4	Emergy used ($\times 10^{20}$ sej)	U	100.45	118.50	154.73	188.73	247.02	217.31	196.54	187.60	219.73
5	Exported emergy ($\times 10^{20}$ sej)	Y	71.40	103.30	135.86	157.22	159.82	142.65	126.26	154.58	147.34
6	Waste emergy ($\times 10^{20}$ sej)	W	8.74	8.95	9.76	10.30	21.00	21.70	25.08	26.50	28.80
7	EIR	$F/(R+N)$	0.124	0.149	0.263	0.480	0.628	0.552	0.470	0.473	0.558
8	ELR	$(N+F)/R$	366	448	598	745	915	817	687	655	813
10	Emergy density ($\times 10^{14}$ sej/m^2)	U/area	6.47	7.00	9.14	10.90	12.80	10.35	9.16	7.39	8.05
11	Emergy used per capita ($\times 10^{14}$ sej/capita)	U/P	355.15	409.03	489.65	563.43	643.32	530.92	465.73	428.80	489.92
12	Electricity per capita ($\times 10^{14}$ sej/capita)	Elect./P	8.23	8.31	11.01	13.14	17.00	17.87	19.28	20.71	24.14
13	Fuel per capita ($\times 10^{14}$ sej/capita)	Fuel/P	17.60	16.04	22.55	23.11	25.36	24.59	26.11	26.79	30.56
14	Emergy/US$ ratio ($\times 10^{12}$ sej/US$)	U/GDP	8.76	8.66	6.64	5.78	4.36	3.18	2.66	3.03	2.78
15	EYR	Y/F	0.77	0.83	0.79	0.72	0.55	0.56	0.56	0.74	0.68
16	ESI ($\times 10^{-3}$)	EYR/ELR	2.10	1.85	1.33	0.97	0.60	0.69	0.81	1.13	0.84
17	Net emergy ($\times 10^{20}$ sej)	$F+R-Y$	21.81	19.23	31.04	52.06	110.49	93.70	85.77	48.39	68.79
18	Net emergy ratio	Net emergy/U	0.217	0.162	0.201	0.276	0.447	0.431	0.436	0.258	0.313
19	Emergy diversity index[a]	$-\sum E_i(\ln E_i)$	1.65	1.42	1.61	1.50	1.47	1.31	1.44	1.42	1.50
20	Emergy development ability[b] ($\times 10^{20}$ sej)	$-\sum E_i(Ep_i)\times U$	166.21	168.48	249.44	282.12	362.19	283.85	283.78	268.09	329.81

[a]The emergy diversity index was calculated using Eq. (8).
[b]The emergy development ability was calculated using Eq. (9).

Macao's emergy development ability has increased since 1983, reaching a peak value of 362×10^{20} sej in 1993, then decreasing to 268×10^{20} sej in 2002, and increasing again to 330×10^{20} sej in 2003 (Fig. 3e).

As demonstrated by Odum, emergy-based indices are very different in cities than in large natural areas, where free renewable resources can be used to support the ecological systems (Lan et al., 2002). This can be seen by comparing the value of an index such as ELR for Macao (813) with that for the US (5.85; Table 7). Although the indices for small, dense areas such as Hong Kong, Singapore, and Macao differ from those for the vast territories of a country such as the US and are not directly comparable, the different values can still provide insights into the relative ecological characteristics of two areas and assist in guiding the development of suitable policies. In Table 7, NER is more an index of locally sustainable production than a true yield ratio. Despite its relatively low state of development and small economy, Nicaragua is a country rich in natural resources and renewable emergy flows. Thus, its EYR is the highest of the regions in Table 7, and its relatively low economic development status produces an extremely low ELR. The country also has the highest ESI of these regions. On the other hand, cities like Macao and the Taipei Basin area that use large amounts of nonrenewable emergies and import much emergy have a very low EYR and a high ELR; as a result, they have a small ESI.

The NER given in the last column of Table 7 is a measure of the overall emergy exchange conditions of a study area. A high NER is indicative of economies that import more emergy than they export, accompanied by increased net emergy welfare.

4.3. Results of the tourism emergy analysis

Gambling in Macao has existed almost from the outset, with gambling legalized in Macao in the 1850s to raise much-needed funding to support colonies such as Timor (Gunn, 1996), and a casino monopoly market that lasted in Macao from the 1930s to 2002; the most recent monopoly concession holder was the Sociedade de Turismo e Diversoes de Macau (STDM), which held this concession from 1962 to 2002. Hong Kong and China do not permit legalized casino gambling, therefore Macao has enjoyed a comparative advantage that has been exceedingly lucrative for the administrative district (McCartney, 2005).

After having a gambling monopoly for more than 60 years, of which the STDM casino monopoly spanned the last two-thirds, the government of Macao chose to open one of the world's most lucrative gambling concessions to international organizations (McCartney, 2005). As a quickly developing industry, tourism brings income but also environmental impacts to an area. In 2003, 11,887,876 tourists visited Macao, an amount equal to about 26 times its population. The majority of visitors came from Mainland China (48.3%), Hong Kong (38.9%), and Taiwan (8.6%). The average visitor spent $189, and stayed for 1.26 days in Macao. In 2003, tourism earned Macao a gross income of $5.21 billion. Taxes from gambling equaled $1.32 billion, an amount equal to 74.9% of the annual revenue (The Statistics and Census Service, 2004). Tourism is estimated to have contributed 65.9% of GDP in 2003, and accounted for 39.3% of the total emergy used. In 2002, Macao represented the world's third-largest gambling market, and the gambling revenues of $3.58 billion in 2003 represented a 27% increase over the 2002 totals

Table 7
Comparison of selected emergy indices for several national economies

Country	U ($\times 10^{20}$ sej)	R ($\times 10^{20}$ sej)	N ($\times 10^{20}$ sej)	F ($\times 10^{20}$ sej)	Y ($\times 10^{20}$ sej)	GDP ($\times 10^{9}$ \$)	Emergy/\$ ($\times 10^{12}$ sej/\$)	EYR	ELR	ESI	NER
Macao (2003, present study)	220.0	0.3	3.6	216.0	147.0	7.9	2.78	0.68	813.00	0.001	0.31
USA (2000)[a]	118000.0	17200.0	68000.0	32600.0	23900.0	9940.0	1.19	0.73	5.85	0.13	0.22
Italy (2002)[b]	20700.0	1210.0	3480.0	16000.0	9300.0	1260.0	1.75	0.58	16.10	0.04	0.38
Sweden (2002)[c]	3700.0	452.0	3080.0	3060.0	2620.0	360.0	1.03	0.86	13.60	0.06	0.24
Nicaragua (1998)[d]	358.0	276.0	40.0	66.7	143.0	2.3	15.8	2.14	0.39	5.53	0.56
Taipei basin (1998)[e]	2080.0	17.4	12.6	2050.0	1760.0	721.0	1.73	0.86	119.00	0.01	0.15

[a]Data provided by Brown (University of Florida, Gainesville, personal communication).
[b]Data from Cialani et al. (2005).
[c]Data from Hagström and Nilsson (2005).
[d]Data from Cuadra and Rydberg (2000).
[e]Data from Huang (2004).

(McCartney, 2005). The liberalization process has greatly magnified Macao's casino revenues, with Macao generating 56% more earnings than the Las Vegas Strip and 196% more than Atlantic City from 450 gambling tables in 2003, putting Macao in a key position to rival both traditional gambling strongholds, particularly as more casino properties open in the future (McCartney, 2005).

Gambling-related travel will contribute to Macao's net consumption in several categories (Gan, 2004):

1. Increasing the number of types of consumption available to the tourists. In Macao, the different gambling options include games of chance (21 types of casino games), greyhound racing, horse racing, the Chinese Lottery, instant lotteries, and sports lotteries (soccer and basketball).
2. Changing the components of consumption by tourists and increasing the gross consumption.
3. Promoting the development of related industries. The booming gambling industry will provide new jobs, and will drive construction, finance, hotels, transportation, restaurants, wholesale and retail sales, and many other economic activities.

Although gambling tourism brings pronounced economic benefits, there is also a need to remain aware of the social and environmental impacts of the associated development. Preliminary research has shown that Macao residents generally do not gamble in the local casinos (McCartney, 2005). Macao is already one of the most densely populated areas in the world, and with 16,000 inhabitants per square km and with the development of large casino complexes and the supporting infrastructures already underway, issues such as rising levels of noise and water pollution, littering, traffic jams, and destruction of the natural environment will become important issues. Of particular importance is the issue of heritage and cultural conservation, with Macao's history dating back more than 450 years to the time when Macao first came under Portuguese administration. The rapid pace of development and limited area in which the development can occur creates an apparent conflict between the transportable "manufactured" experiences offered by the casino industry and the "authentic" experiences sought by those who want to explore Macao's heritage and culture (McCartney, 2005).

The statistical data for Macao's tourism sector are illustrated in Fig. 4 and summarized in Table 8. The proportions of tourism and gambling income were higher in monetary terms than on an emergy basis (Table 8) because the environmental resource has been fully accounted for in emergy synthesis, widening the accounting base. In monetary terms, only man-made capital is accounted for. The tourism indicators increased steadily from 1983 to 2003, except from 1997 to 1999. From 1997 to 2000, development related to gambling and tourism income decreased while criminal activity increased, and these changes influenced tourist income. Since 2000, the economy of Macao has maintained a robust growth rate and sustained prosperity, both of which have benefited from the gambling and tourism industries.

The analysis in Sections 4.1 and 4.2 demonstrated that more emergy is imported than exported. The number of tourist visits to Macao has increased steadily since 1983. In 1983, there were only 4.1 million tourists, but that total reached 11.9 million in 2003. The number of the tourists amounted to 14.5 times Macao's population in 1983, but this ratio increased to 26.5 in 2003 (Table 8).

During the 1980s, the manufacturing industry contributed important benefits to Macao's economy, particularly after China opened its doors to the world market. But since 1990, this sector lost its advantage due to competition with Chinese and southeast Asian rivals. As a result, gambling became more and more important to Macao's economy and became an increasingly large proportion of the government's revenues. Fig. 4a shows the trends in GDP, tourism income, gambling income, and government revenues from 1983 to 2003; all four curves show parallel changes, with slight differences in the slopes of the curves.

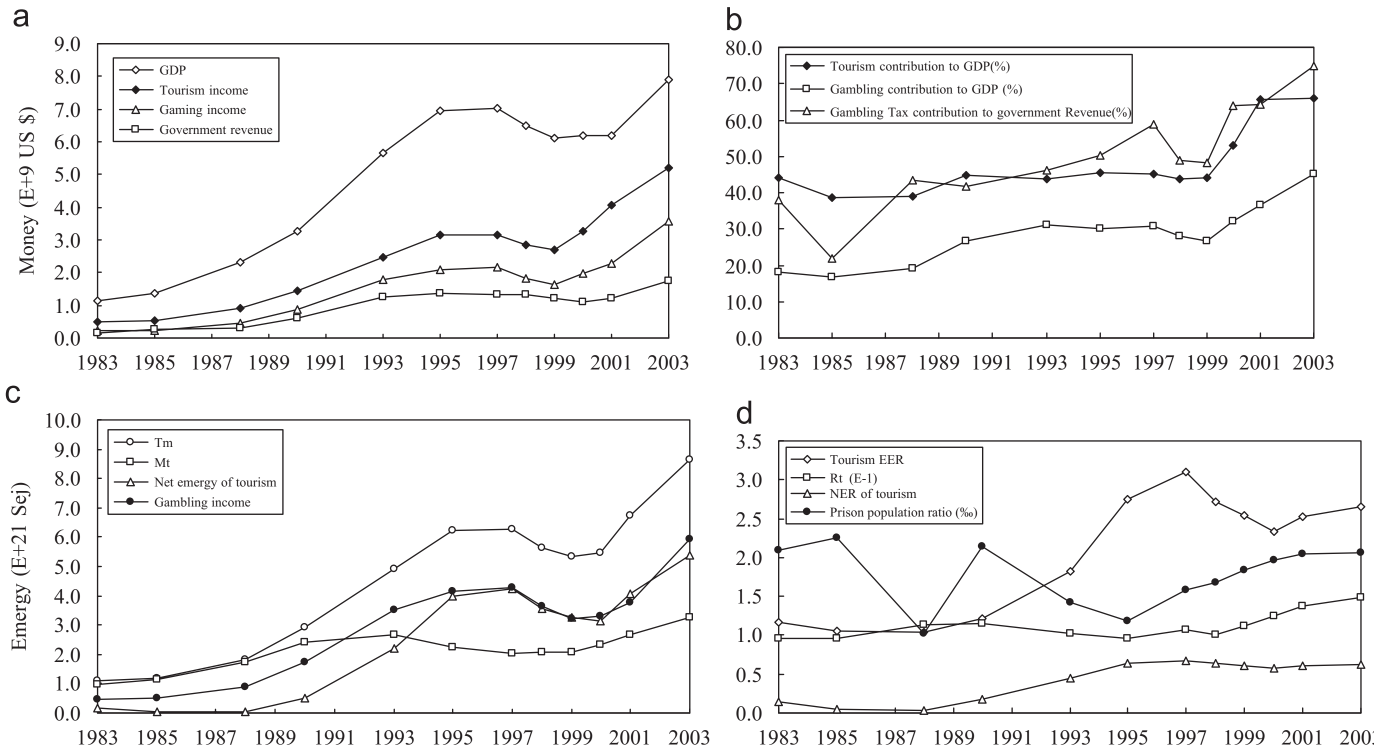

Fig. 4. Economic and emergy statistics for Macao from 1983 to 2003. (a) GDP, tourism, gambling income, and government. (b) Percentage contributions of tourism, gambling income, and gambling tax to government revenues. (c) T, M_t, gambling income, and net tourism emergy. (d) EER, R_t, NER of tourism, and prison population rate.

Fig. 4b indicates that the percentage of GDP accounted for by tourism increased from 44% in 1983 to 65.9% in 2003; during the same period, the proportion of GDP accounted for by gambling revenues rose from 18.3% to 45.3%, and the ratio of gambling taxes to government revenues increased from between 21.8% and 38% to 74.9%. The emergy of tourism increased from 11.1×10^{20} sej in 1983 to 86.5×10^{20} sej in 2003. During the same period, tourist consumption emergy increased from 9.56×10^{20} sej to 32.6×10^{20} sej.

Fig. 4c shows T_m, M_t, gambling income, and net emergy of tourism from 1983 to 2003. Emergy peaked between 1995 and 1997, decreased briefly, then increased once more.

The emergy received from Macao's tourism represents the emergy converted from the monetary income of tourism (T_m), and the emergy of tourist consumption is the emergy provided to the tourists (M_t). Fig. 4d shows the tourism EER, R_t, and NER from 1983 to 2003. Tourism EER increased from 1.16 in 1983 to 3.1 in 1997, then declined to 2.3 in 2000, and finally rose again to 2.66 in 2003. This means that in 2003, a visitor who consumed 1 sej of emergy services in Macao spent 2.66 sej of embodied equivalent emergy money (em$). Tourism's net emergy was small between 1983 (1.5×10^{20} sej) and 1988 (6.3×10^{20} sej), then rose quickly to 42.3×10^{20} sej in 1993, decreased to 31.2×10^{20} sej in 2000, and finally increased to a peak of 53.9×10^{20} sej in 2003 (Fig. 4c). The ratio (R_t) of the emergy that tourists consumed (M_t) to emergy used (U) slowly increased, from 0.096 in 1983 to 0.148 in 2003 (Fig. 4d). By dividing the net emergy of tourism by the embodied emergy (T_m), the NER of tourism is obtained; this parameter expresses the benefits of Macao's tourism, with a higher ratio showing a greater net emergy benefit. The NER of tourism decreased from 0.14 in 1983 to 0.03 in 1988, then rose steadily to 0.63 in 2003 (4.5 times the 1983 value). The prison population rate (number of prisoners per 1000 citizens) varied between years before 1995, then increased from 1.18‰ in 1995 to 2.06‰ in 2003 (Fig. 4d), following a similar pattern to the statistics for gambling; this suggests a relationship between gambling development and the social cost of crime.

4.4. Results of statistical analyses

Table 9 shows the results of our statistical analysis (correlation coefficients between the various emergy statistics that we calculated). The 15 primary indicators exhibited significant positive and negative correlations, or an absence of significant correlations, depending on the specific combination of indicators being compared:

(1) *Positively correlated indicators*: These indicators represent indices that tend to increase as time goes on. The following indicators were positively correlated with development: imported emergy, emergy used (U), exported emergy, EIR, ELR, average emergy used, average electricity emergy used, average fossil fuel used, and the ratio of electricity to U.

Table 8
Statistical data and emergy flows for Macao's tourism and gambling sector from 1983 to 2003

Item	1983	1985	1988	1990	1993	1995	1997	1998	1999	2000	2001	2003
Population of Macao	282,843	289,704	315,997	334,961	383,984	409,300	422,000	422,304	429,600	437,500	434,096	448,495
GDP ($\times 10^9$ US$)	1.15	1.37	2.33	3.26	5.67	6.94	7.01	6.50	6.10	6.19	6.19	7.90
Tourist visits	4,101,040	4,181,937	5,542,940	5,942,210	5,997,600	5,989,200	7,000,400	6,948,500	7,443,900	91,62,600	10,279,000	11,887,900
Tourist visits/population of Macao	14.5	14.4	17.5	17.7	15.6	14.6	16.6	16.5	17.3	20.9	23.7	26.5
Length of stay (days)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.4	1.3	1.3	1.26
Tourism ($\times 10^9$ US$)[a]	0.505	0.530	0.912	1.46	2.48	3.15	3.16	2.84	2.70	3.28	4.05	5.21
Gambling ($\times 10^9$ US$)[b]	0.210	0.230	0.443	0.869	1.77	2.09	2.16	1.83	1.63	1.99	2.26	3.58
Tourism to GDP ratio	0.440	0.387	0.391	0.448	0.437	0.454	0.451	0.437	0.442	0.530	0.655	0.659
Gambling to GDP ratio	0.183	0.168	0.190	0.266	0.311	0.301	0.308	0.282	0.268	0.321	0.365	0.453
P_2 ($\times 10^{12}$ sej/US$)	2.20	2.22	2.00	2.00	1.98	1.98	1.98	1.98	1.98	1.66	1.66	1.66
P_1 ($\times 10^{12}$ sej/US$)	8.76	8.66	6.64	5.78	4.36	3.13	2.66	3.18	3.06	3.03	3.12	2.78
T_m ($\times 10^{20}$ sej)	11.10	11.80	18.20	29.20	49.10	62.40	62.60	56.30	53.40	54.50	67.33	86.50
Gambling ($\times 10^{20}$ sej)	4.61	5.11	8.87	17.40	35.00	41.40	42.70	36.30	32.40	33.10	37.54	59.40
Gambling to U ratio (US$ basis)	0.183	0.168	0.190	0.266	0.311	0.301	0.308	0.282	0.268	0.321	0.365	0.453
Gambling to U ratio (sej basis)	0.046	0.043	0.057	0.083	0.133	0.176	0.228	0.175	0.173	0.176	0.194	0.270
Tourism EER	1.16	1.05	1.04	1.21	1.83	2.76	3.10	2.71	2.55	2.34	2.52	2.65
R_t	0.096	0.095	0.113	0.114	0.102	0.096	0.108	0.100	0.112	0.124	0.138	0.148
M_t ($\times 10^{20}$ sej)	9.56	11.23	17.57	24.16	26.88	22.65	20.17	20.74	20.97	23.34	26.67	32.58
Net emergy of tourism[c] ($\times 10^{20}$ sej)	1.54	0.57	0.63	5.04	22.22	39.75	42.43	35.56	32.43	31.16	40.66	53.92
NER of tourism[d]	0.14	0.05	0.03	0.17	0.45	0.64	0.68	0.63	0.61	0.57	0.60	0.62
Government revenues ($\times 10^8$ US$)	1.55	2.76	3.02	6.20	12.63	13.50	13.13	13.11	12.34	10.98	12.22	17.60
Gambling taxes ($\times 10^8$ US$)	0.59	0.60	1.31	2.59	5.84	6.77	7.73	6.41	5.97	7.04	7.83	13.19
Ratio of gambling taxes to government revenues[e]	0.38	0.22	0.43	0.42	0.46	0.50	0.59	0.49	0.48	0.64	0.64	0.75
Prison population rate[f] (‰)	2.09	2.25	1.02	2.15	1.42	1.18	1.57	1.68	1.84	1.97	2.04	2.06

[a]Tourism refers to the total expenditure by tourists in Macao's domestic market.
[b]Gambling represents the gambling expenditures of tourists in Macao's casinos.
[c]Net emergy of tourism is the result of $T - M_t$.
[d]NER of tourism is the result of net emergy of tourism divided by T.
[e]The gambling tax to revenue ratio represents gambling taxes divided by total government revenues.
[f]The prison population rate is the ratio of the prisoner population to the total population.

Table 9
The results of correlation analysis (Pearson's coefficient) for the primary emergy flows and indices for Macao

No.	Emergy index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Imported emergy															
2	Emergy used (U)	*														
3	Exported emergy	*	*													
4	Ratio of renewable resources to U															
5	EIR	*	*	*												
6	ELR	*	*	*		*										
7	Ratio of wastes to U															
8	Average emergy used	*	*	**		*	*	***								
9	Average electrical emergy	*	*	*		*	**	**								
10	Average fuel emergy	*	*	*		*	*			*						
11	Emergy/$ ratio	****	****	***		****	****			****	****					
12	Emergy yield ratio															
13	Ratio of electricity emergy to U			**		***		*		*	*	****				
14	ESI	****	****	***		****	****		****	***	***	*				
15	Net emergy												****		****	

*Positive correlation, significant at $P<0.01$ (two-tailed test).
**Positive correlation, significant at $P<0.05$ (two-tailed test).
***Negative correlation, significant at $P<0.05$ (two-tailed test).
****Negative correlation, significant at $P<0.01$ (two-tailed test).

(2) *Indicators with no significant correlation*: The following indicators were not correlated with development: the ratio of renewable resources to emergy used, and the ratio of wastes to emergy used.
(3) *Negatively correlated indicators*: These indicators represent indices that tend to decrease as time goes on. The following indicators were negatively correlated with development: the emergy/$ ratio, the EYR, ESI, and net emergy.

For a stable system, the input emergy must equal the output emergy: $Y = R+N+F$ (Brown and Ulgiati, 1997). In contrast, in an expanding system such as Macao, the emergy output should be less than the input emergy (i.e., $Y < R+N+F$) and the emergy storage should increase (Huang, National Taipei University, personal communication). On the other hand, for a degrading or shrinking city, the outflow emergy should exceed the inflow emergy. The direction in which a system is changing thus depends on its emergy balance.

Since the gross emergy storage is not easy to determine for a system as complex as Macao, the storage of emergy since 1983 can be obtained by summing the net emergy during the study period. This amounts to about 3260×10^{20} sej according to the data in Table 6, and this amount is about 14.8 times the emergy used in 2003. The increased emergy was embodied in roads, buildings, and other urban infrastructure that enriched the city's assets.

5. Conclusions

Compared with mature ecosystems, urban ecosystems are relatively immature due to their rapid growth and inefficient use of resources. In addition, cities rely more strongly on ecosystems beyond the city limits than is the case for more self-contained natural ecosystems. As cities draw more and more resources from distant areas, they also accumulate large amounts of materials (Huang and Hsu, 2003), including wastes discharged into the surrounding systems. Odum (1989, 1994) has observed that cities are among the most heterotrophic ecosystems in the biosphere, and this also appears to be true of Macao. From the point of view of systems ecology, cities are self-regulating systems and may be seen as super-organisms, created for the benefit of human beings and for sustaining their livelihood (Odum, 1989). Prigogine pointed out that systems that are far from equilibrium (i.e., dissipative structures) can exist only as long as the system is sustained by a continual flow of energy or matter (i.e., negative entropy) through the system (Odum, 1994).

Our research demonstrated that by relying on an attractive gambling industry and an imbalance between imports and exports, Macao has absorbed large amounts of emergy through negative entropy inflows to support not only its survival, but also its booming development. EER has proven to be a useful indicator for studying emergy exchanges; an EER value of more than 1 means that the exchange brings an emergy surplus to the system, and this surplus can also be used in Macao's tourism industry. The imported emergy (F), emergy density, fuel and electricity emergy, and ELR of cities should be much higher than those of natural systems. Denser cities usually have a very high ELR due to their lack of internal natural resources available for use. In 2003, the ELR of Macao was 813, which was much greater than the corresponding values for the US (5.85), Italy (16.10), and Sweden (13.60).

With its large population and scarce resources, Macao must protect its emergy surplus and diversity when exchanging materials and emergy with its primary supply regions, and must export its abundant tourism and services to nearby regions. How and on what scale the emergy flow from nearby regions (especially China, Hong Kong, and Taiwan) influences Macao remains a topic for future research.

For a micro-ecosystem such as that of a small city, oscillations in emergy can always be found (Odum, 1996); this variability reflects the instability and fragility of the system. Statistical analysis revealed that the emergy-based indicators in the present study could be divided into three categories (namely, positively and negatively correlated indicators, and noncorrelated indicators) according to their correlation with development trends.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jenvman.2007.04.009.

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