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Emergy Synthesis for Three Main Industries in Wuyishan City, China

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ABSTRACT. Emergy synthesis is an objective method for evaluating the resource consumption by industrial development and the resulting environmental impacts. In this study, we apply emergy synthesis to account for the energy and material flows of three main industries in China's Wuyishan City, i.e. the tourism, tea, and bamboo industries. We calculate seven indices: renewable input ratio, emergy self-support ratio, emergy investment ratio, emergy density, emergy money ratio, emergy yield ratio, and environmental loading ratio. The results show that the continuous development of tourism industry is mainly resulted from the increase in its purchased resources, the tea industry's development has been relatively stable, and the bamboo industry depends greatly on non-renewable resources but has considerable development potential. The results suggest that tourism is the most environment-friendly one. Based on our analysis, we propose two sustainable development strategies: the promotion of intercropping in tea and bamboo plantations and the development of an advanced value-added bamboo production chain.

Keywords: emergy, bamboo industry, tea industry, tourism, Wuyishan City

1. Introduction

Wuyishan is a small city in the Fujian Province, located in southeastern China. The city has been named one of UNESCO's Double World Heritage sites (Culture and Nature) since 1997 for its rich and distinctive history and landscape. The protection of the city's natural resources and environment is therefore important. However, the environment has suffered from increasingly severe damages because of rapid economic development. Assessment of industrial development is thus needed to assist the city government to analyze the tradeoffs between environmental protection and economic development.

The approaches to study an industry's environmental impacts can be classified into two categories: (1) economic evaluations based on perceived monetary gains, and (2) energy evaluations based on ecosystem processes and pathways (Bardi, 2002). Rather than considering an industry's environmental effects (Damigos, 2006), conventional economic evaluations have mainly focused on the assessment of the economic characteristics of an industry, such as costs and benefits (Bennett and Blaney, 2003), social value (Jun et al., 2010), global strategic alliances (Ojah, 2007), industrial turnover (Misund et al., 2008), and the value of industrialization (Ming and Hin, 2006). Although these economic evaluations can directly evaluate an industry's monetary contribution to human society, non- market factors such as environmental impacts and ecosystem services generally cannot be assessed by means of merely economic approaches. To address this problem, alternative simulation approaches have been developed, including the assessment of an individual's willingness-to-pay for environmental services (Costanza et al., 1997) and the cost to restore damaged ecosystems to their original state (Bell, 1997). All these methods are based on the assumption that ecosystem services could be marketed. The assumption leads to subjective estimation of the values of such services.

Compared to these alternative approaches, methods based on energy evaluation are more objective because they can deal with the hierarchy of different kinds of energy. Odum (1996) proposed the concept of "energy quality" and defined energy quality in terms of emergy as the "embodied energy". The theoretical background and detailed mathematical formulations for emergy analysis can be found in the literature (Odum, 1996; Brown and Ulgiati, 1997; Odum et al., 2000).

The emergy concept was widely used to analyze both ecosystems (Brown and Ulgiati, 1999; Tilley and Brown, 2006) and economic systems (Huang et al., 1995, 2006; Chen et al., 2006; Zhang et al., 2009a, b). In an industrial context, emergy was used to analyze agriculture (Martin et al., 2006; Zhang et al., 2007b), manufacturing (Odum, 2000; Brown and Ulgiati, 2002; Wang et al., 2005), and services (Federici et al., 2003; Lei and Wang, 2006). However, emergy was only used in the ecological evaluation of a particular industry, the ecological comparisons of industries of different regions, or the compa-

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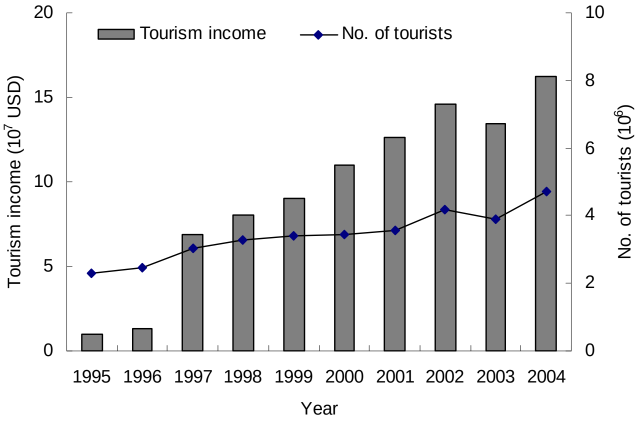

Figure 1. Development of Wuyishan's tourism industry since 1995 (data source: Wuyishan Statistical Bureau, 1996-2005).

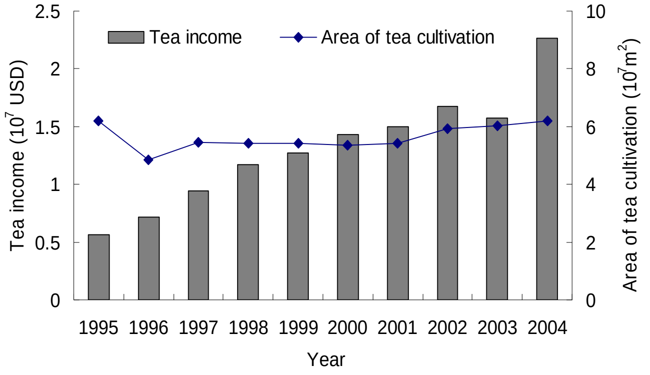

Figure 2. Development of Wuyishan's tea industry since 1995 (data source: Wuyishan Statistical Bureau, 1996-2005).

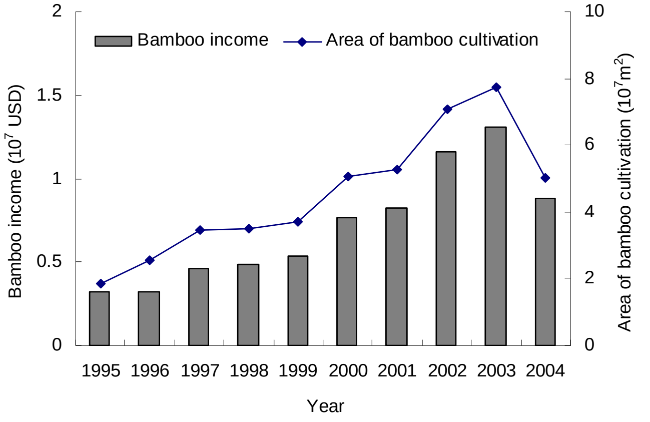

Figure 3. Development of Wuyishan's bamboo industry since 1995 (data source: Wuyishan Statistical Bureau, 1996-2005).

risons of the ecological and economic benefits and costs from different industries in the same region (Lefroy and Rydberg, 2003). In fact, emergy analysis can also be applied to evaluate resource consumption and services for different industrial systems using common units (Odum, 1996), which previous studies did not reflect.

Therefore, seven common indices in emergy analysis will be applied in this study to compare the ecological and economic benefits and costs of different industries of Wuyishan City. Specifically, three main industries (i.e. tourism, tea, and bamboo) will be evaluated for the period of 1995 to 2004.

2. Study Area and Data

Wuyishan City, which covers a total area of 2813.91 km^2, is located close to the Tropic of Cancer (117°37’ E to 118°19’ E, 27°27’ N to 28°05’ N). The city is in a sub-tropical region, with a humid monsoon climate. It has an average annual temperature of 17.9 °C and an average annual precipitation of around 1900 mm, concentrated in the spring and summer. The mean solar radiation in this region is 4.6×10^9 J/(m^2·yr). Due to the growing environmental impacts of industrial activities, the Wuyishan Nature Reserve's ecosystem has become fragmented, and the biodiversity has been seriously affected. For example, the forest cover decreased from 70 to 53% during the 1990s. The city's economy, and especially the tourism, tea, and bamboo industries, has developed rapidly in recent years.

Because of the city's rich tourism resources, tourism plays a leading role in Wuyishan's economic system. Wuyishan was named “China's excellent tourist city” by the National Tourism Administration of China in 1999. The revenues contributed by tourism account for nearly half of Wuyishan's total revenues each year (Figure 1). Wuyishan's traditional tea industry has a history of more than 1000 years. By the end of 1994, tea plantations accounted for 30% of the total farmland, with steadily growing income (Figure 2). However, the planting and manufacturing technologies used by this industry were relatively primitive until around 2002, when small tea factories were closed, merged with other factories, or transformed by the city's government. Bamboo is also a traditional industry in Wuyishan, particularly in the area surrounding the Wuyishan Nature Reserve. Because bamboo quickly regenerates after harvesting, its growth cycle is short: bamboo farmers only need to provide some labor and fuel for harvesting or transportation equipment. Because of its low inputs, the bamboo industry is generally considered to be an appropriate industry for the city. Its economic benefits and planted area have increased significantly (Figure 3). Because of their importance, we have chosen the tourism, tea, and bamboo industries to represent the city's main industries. All data used in this study was provided by the Wuyishan Statistical Bureau (1996 ~ 2005).

3. Methodology

3.1. Emergy Synthesis

Emergy synthesis integrates dynamic and comparative analysis based on the principles of emergy accounting. The dynamic analysis provides a reliable evaluation of the system during a given period, and proves to be very useful in understanding temporal trends in sustainability (Tilley and Brown, 2006; Lei and Wang, 2008). Comparative emergy analysis is a methodology that compares the characteristics of various properties of similar systems, such as the same type of system in different regions (Cohen et al., 2006) or different systems with-in a given region (Lefroy and Rydberg, 2003; Martin et al., 2006; Zhang et al., 2007b).

Odum (1996) put forward the theory of emergy analysis, and introduced two key terms: emergy and transformity. Emergy of one type (usually solar) is defined as the sum of all flows of available energy that is consumed, directly or indirectly, to make a product. Each of these energies is expressed in standardized energy unit (usually solar emjoules, sej). Odum (1996) described the "available energy" as exergy. When flows are expressed in mass unit (e.g., g), the conversion factor is expressed in sej/g and is named the specific emergy. The transformity of a product (τ) equals to its emergy divided by the available energy, and the product's emergy can therefore be expressed as below (Odum, 1996):

$$Em = \tau \times Ex \tag{1}$$

where Em is the product's emergy (sej) and Ex is the available energy (exergy, J). The primary source of energy for all terrestrial ecosystems is sunlight, which drives the rain, the wind, and most Earth cycles. To reflect the importance of solar energy to support most ecosystems, the varied qualities of energy content inherent in the material and energy flows of an urban industrial system is calculated by multiplying the energy content or mass of a flow by its solar transformity value. The transformity reflects the energy's qualitative value, thereby obtaining its total solar emergy in solar emjoules (Huang et al., 2006). During the past three decades, Odum and his colleagues have calculated transformities for a wide range of products and services. Detailed references now allow the calculation of emergy values for most forms of energy and resources (Odum, 1996; Brown and Bardi, 2001; Brown and Ulgiati, 1997, 2004). The larger the transformity, the more solar energy is required to make a product, and the higher is its position in the energy hierarchy of the biosphere (Odum, 1988, 1996). Because economic values can also be expressed in emergy terms, emergy synthesis thus provides an integrated evaluation of the ecological and economic values that flow through a system, making it possible to study an urban industrial system in an integrated manner. Ideally, emergy analysis should use transformity values that have been specifically calculated for the study area, but emergy research in China is still in its early days, and no Chinese transformity values are available in the present study; as a result, we used values from the international research literature. Although this approach may bias our results to some extent, the results should nonetheless provide acceptable relative values that support comparisons of the three Industries.

The basic emergy flows can be quantified based on transformities. A specific industrial system can be driven by both natural resources and economic investments, which can be renewable or non-renewable. In our analysis, we grouped the inputs of the three industries into four categories: free renewable resources from the environment (*RR*) (e.g. sunlight, rain, wind, and Earth cycles), free non-renewable resources from the environment (*NR*) (e.g. topsoil loss and biodiversity loss), purchased non-renewable inputs (*NP*) (e.g. fossil fuels and inorganic fertilizers), and purchased renewable inputs (*RP*) (e.g. organic manure and seed purchased from outside of the study system). The total emergy use (*U*) can then be expressed as follows:

$$U = RR+NR+NP+RP \tag{2}$$

3.2. Evaluation Indices

Based on the quantification of emergy flows, a series of indices can be calculated by emergy synthesis. Various system evaluation indices have been proposed by Odum and his colleagues (Odum, 1996; Brown and Ulgiati, 1997; Cohen et al., 2006). Different indices can be selected to construct index systems that are suitable for specific research objectives (Odum, 1996; Brown and Ulgiati, 1997, 1999; Lan et al., 2002; Chen et al., 2006; Zhang et al. 2009b). Currently, the city's primary problem is how to reduce the consumption of non-renewable resources and the resulting damage to the ecosystem without adversely affecting economic growth. We did not calculate the emergy of wastes in this study, since environmental pollution by the three industries is minor. The basic indices of interest associated with the industrial systems are as follows:

$$\textit{Renewable input ratio (RIR)} = (RR+RP) / U \tag{3}$$

This index represents the proportion of the total emergy use accounted for by renewable inputs, and therefore reflects the renewable contribution to the overall industrial system. Industrial development relies more on renewable resources as this index increases:

$$\textit{Emergy self-support ratio (ESR)} = (RR+NR) / U \tag{4}$$

This index represents the ratio of the emergy of all local environmental inputs to the total emergy use, and therefore reflects the environmental contribution to a productive system. Industries with higher *ESR* values depend more on free environmental resources and can therefore increase their productivity when economic investment increases:

$$\textit{Emergy investment ratio (EIR)} = (NP+RP) / (RR+NR) \tag{5}$$

This index represents the ratio of the purchased emergy inputs received from the economy to the free emergy provided by the environment. The lower the ratio, the lower the economic costs. Industries with low *EIR* values tend to prosper in the market because their funding requirements are low. The higher the ratio, the higher the economic development level of an industry and the higher the economic investment that is required:

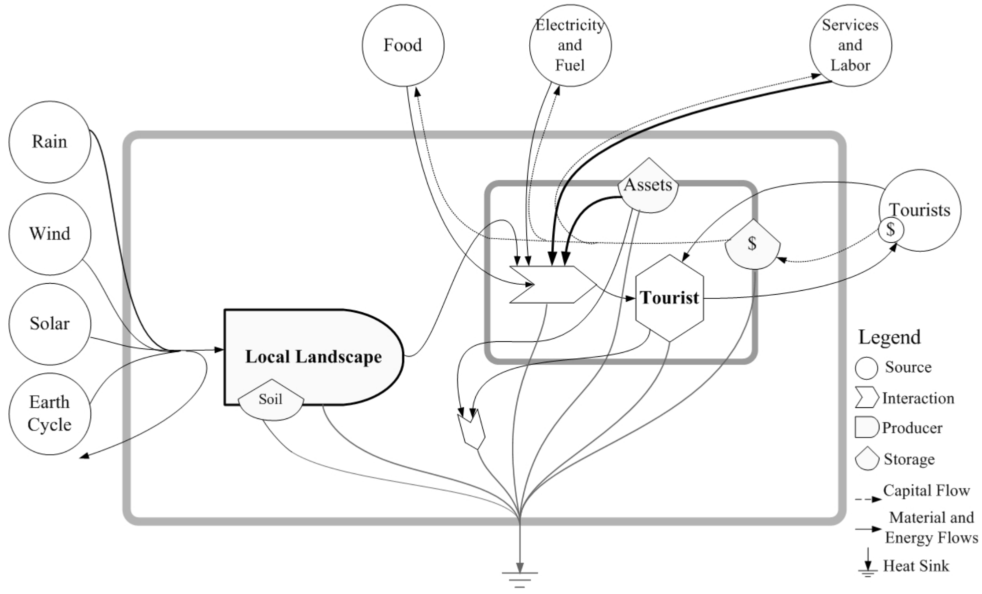

Figure 4. Diagram of the aggregated energy and material flows for Wuyishan's tourism industry.

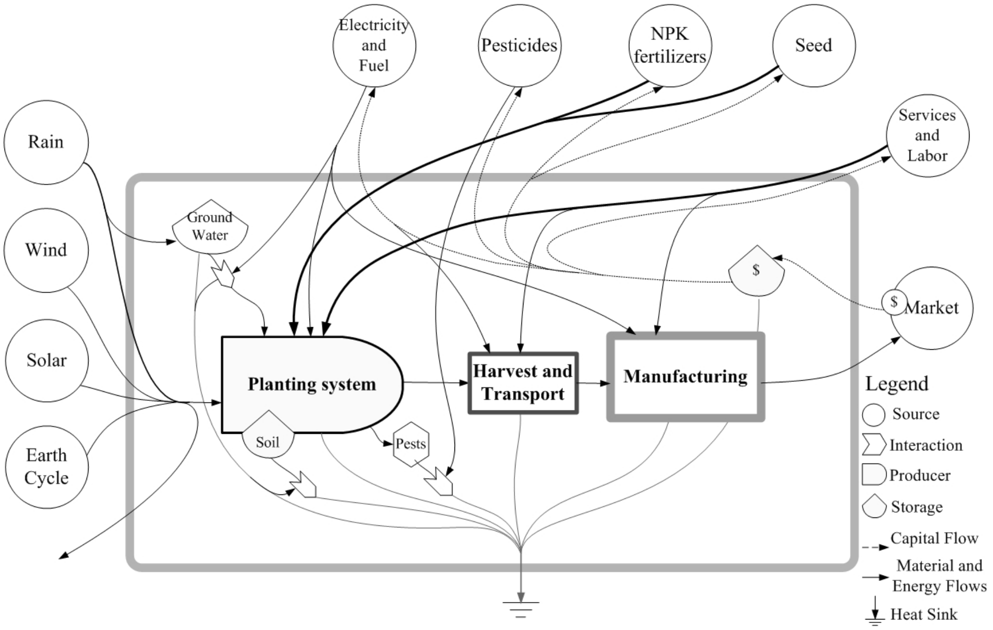

Figure 5. Diagram of the aggregated energy and material flows for Wuyishan's tea industry.

$$Emergy\ density\ (ED) = U / Area \tag{6}$$

This index represents the ratio of total emergy use to the area used by the industry. It therefore indirectly indicates the industry's environmental impact. Industries with higher *ED* values cause more flux per unit area and therefore represent greater environmental impacts.

$$Emergy\ money\ ratio\ (EMR) = U / GDP \tag{7}$$

This index represents the ratio of total emergy use to the gross domestic product (*GDP*) in a given year. Because the money is measured as US dollar, this index can also be expressed as the emergy/$ ratio (*Em*/$). It therefore represents the amount of emergy used to generate one dollar of economic production by the industrial system and can be used to characterize the industry's consumption intensity. The larger the *EMR* value, the higher the industry's resource-use intensity. An industry with a large *EMR* value is usually relatively undeveloped, and loses emergy when trading with other Industries. In general, *EMR* decreases annually due to a combination of inflation and economic development, and due to increasing efficiency of resource usage as an industry develops:

Table 1. Emergy Evaluation Table for Wuyishan's Tourism Industry in 2004

Inputs	Item	Annual flow (unit/yr)	Transformity (sej/unit)	Reference	Emergy (10^{17} sej/yr)
RR	Sun (J)	1.90×10^{18}	1.00	Odum et al. (2000)	19
	Rain, chemical (J)	4.12×10^{15}	3.05×10^{4}		1260
	Rain, geo-potential (J)	2.29×10^{15}	4.70×10^{4}		1080
	Wind (J)	5.07×10^{13}	2.45×10^{3}		1.24
	Earth cycles (J)	8.16×10^{14}	5.80×10^{4}		473
NR	Net topsoil loss (J)	4.50×10^{11}	1.24×10^{5}	Brandt-Williams (2002)	0.558
NP	Electricity (J)	5.09×10^{13}	2.69×10^{5}	Brown and Bardi (2001)	137
	Fuel (J)	4.42×10^{16}	1.06×10^{5}	Odum et al. (2000)	4690
RP	Meat, fish, and eggs (J)	5.09×10^{11}	9.15×10^{5}	Brandt-Williams (2002)	4.66
	Vegetables and fruits (J)	8.48×10^{11}	1.43×10^{5}	Brandt-Williams (2002)	1.21
	Labor (J)	2.62×10^{14}	3.80×10^{5}	Lan et al. (2002)	995
	Total yield, Money ($)	1.62×10^{8}			

Notes: RR, Free renewable natural resources inputs; NR, Free non-renewable natural resources inputs; NP, Purchased non-renewable inputs; RP, Purchased renewable inputs.

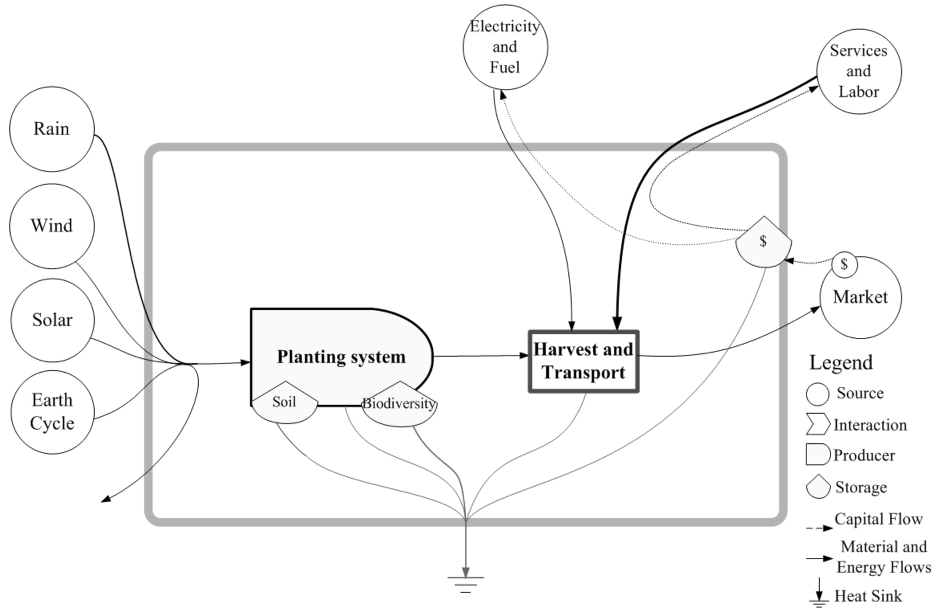

Figure 6. Diagram of aggregated energy and material flows for Wuyishan's bamboo industry.

$$\text{Emergy yield ratio } (EYR) = Y / (NP+RP) \qquad (8)$$

This index represents the total emergy yield, which is considered to equal to the total emergy use (*U*) divided by the purchased emergy inputs from outside the industrial system. *EYR* therefore reflects the economic efficiency of an industrial system. The higher its value, the greater the return obtained per unit of emergy invested:

$$\text{Environmental loading ratio } (ELR) = (NR+NP) / (RR+RP) \qquad (9)$$

This index represents the ratio of total emergy in the form of non-renewable inputs to total emergy in the form of renewable inputs. It can be used as an indicator of the pressure an industrial system imposes on the environment. The higher this ratio, the greater the stress on the environment.

4. Results

4.1. Emergy Analysis

Based on the emergy circuit symbols defined by Odum (1996), we created diagrams for Wuyishan's three key industries (Figures 4, 5, and 6). These diagrams have been aggregated for the sake of simplicity, while still showing the main inputs and yields in each system. We constructed evaluation tables for the actual flows of energy, materials, and labor based on these diagrams. Tables 1 to 3 show the accounting results for Wuyishan's three key industrial systems in 2004.

We evaluated the emergy used by the three industrial systems from 1995 to 2004 according to the parameters and transformity values listed in Tables 1, 2, and 3. The emergy of free renewable natural resources (*RR*), free non-renewable natural resources (*NR*), purchased non-renewable inputs (*NP*), and pur-

Table 2. Emergy Evaluation Table for Wuyishan's tea Industry in 2004

Inputs	Item	Annual flow (unit/yr)	Transformity (sej/unit)	Reference	Emergy (10^{17} sej/yr)
RR	Sun (J)	2.09×10^{17}	1.00	Odum et al. (2000)	2.09
	Rain, chemical (J)	4.55×10^{14}	3.05×10^{4}		139
	Rain, geo-potential J)	2.53×10^{14}	4.70×10^{4}		119
	Wind (J)	5.59×10^{12}	2.45×10^{3}		0.1.37
	Earth cycles (J)	9.00×10^{13}	5.80×10^{4}		52.2
NR	Net topsoil loss (J)	7.45×10^{10}	1.24×10^{5}	Brandt-Williams (2002)	0.1
NP	Electricity (J)	3.87×10^{12}	2.69×10^{5}	Brown and Bardi (2001)	11.5
	Fuel (J)	2.14×10^{13}	1.06×10^{5}	Odum et al. (2000)	22.7
	Pesticides (g)	1.36×10^{8}	1.48×10^{10}	Brandt-Williams (2002)	20.1
	Nitrogen (g)	2.24×10^{9}	2.41×10^{10}	Brandt-Williams (2002)	540
	Phosphate (g)	5.34×10^{8}	2.20×10^{10}	Brandt-Williams (2002)	117
	Potassium (g)	5.11×10^{8}	1.74×10^{9}	Brandt-Williams (2002)	8.88
RP	Seeds ($)	4.06×10^{14}	1.18×10^{13}	Jiang et al. (2008)	4.79
	Labor (J)	1.07×10^{13}	3.80×10^{5}	Lan et al. (2002)	40.7
	Total yield, money ($)	2.26×10^{7}			

Notes: RR, Free renewable natural resources inputs; NR, Free non-renewable natural resources inputs; NP, Purchased non-renewable inputs; RP, Purchased renewable inputs.

Table 3. Emergy Evaluation Table for Wuyishan's Bamboo Industry in 2004

Inputs	Item	Annual flow (unit/yr)	Transformity (sej/unit)	Reference	Emergy (10^{17} sej/yr)
RR	Sun (J)	1.69×10^{17}	1.00	Odum et al. (2000)	1.69
	Rain, chemical (J)	3.68×10^{14}	3.05×10^{4}		112
	Rain, geo-potential (J)	2.04×10^{14}	4.70×10^{4}		96
	Wind (J)	4.52×10^{12}	2.45×10^{4}		1.11
	Earth cycles (J)	7.28×10^{13}	5.80×10^{4}		42.2
NR	Biodiversity loss (m^2)	1.51×10^{7}	4.90×10^{14}	Odum (1994)	73800
	Net topsoil loss (J)	2.01×10^{10}	1.24×10^{5}	Brandt-Williams (2002)	0.02
NP	Fuel (J)	8.28×10^{12}	1.06×10^{5}	Odum et al. (2000)	8.78
RP	Labor (J)	4.49×10^{11}	3.80×10^{5}	Lan et al. (2002)	1.71
	Total yield, money ($)	8.79×10^{6}			

Notes: RR, Free renewable natural resources inputs; NR, Free non-renewable natural resources inputs; NP, Purchased non-renewable inputs; RP, Purchased renewable inputs.

chased renewable inputs (*RP*), and the corresponding values of the indices described in section 3.2, were calculated for a 10-year time horizon. Tables 4, 5, and 6 present the results of these calculations. The calculated *RR*, *NR*, *NP*, and *RP* values for the three industries show the resource-use characteristics of each industry and their temporal trends from 1995 to 2004 (Figure 7).

Tourism mainly uses *RR* and *NP*, which together account for between 66 and 93% (with a mean of 80%) of the total emergy used. The purchased non-renewable resources increased more rapidly during the 10 years than was the case for the other resources. In 2004, *NP* accounted for about 60% of the total, compared with only 7% in 1995. The tea and bamboo industries presented different trends from tourism. Their emergy structures changed slightly and steadily. However, the tea and bamboo industries mainly depended on *NP* and *NR*, respectively. The *NP* and *RR* values for the tea industry accounted for more than 90% of the total, with *NP* accounting for between 57 and 73% (with a mean of 64%) of the total. Wuyishan's bamboo industry differed significantly from the other industries because *NR* accounted for more than 95% of the total emergy used from 1995 to 2004, and includes biodiversity and topsoil loss.

4.2. Analysis of the Seven Emergy Indices

4.2.1. Renewable Input Ratio (RIR)

Tables 4 to 6 show that the *RIR* values of the three industries were clearly different from each other. Tourism has the highest *RIR*, but this value decreased from more than 0.9 in 1995 to 0.4 in 2004. It indicates that renewable resources no longer play as important a role in the development of tourism as they did 10 years earlier. The development of tourism increasingly depends on non-renewable resources, although renewable resources remain more important to tourism than to the tea and bamboo industries. The *RIR* of the tea industry initially increased from about 0.3 to about 0.4, and then decreased back to 0.3. The *RIR* of the bamboo industry remained continuously low (< 0.01) because of its high dependence on the use of non-renewable natural resources.

Table 4. Indices for Wuyishan's Tourism Industry from 1995 to 2004

Index	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Flows										
RR (sej)	2.93×10^{20}	2.18×10^{20}	2.88×10^{20}	3.39×10^{20}	2.78×10^{20}	$2.73\times10^{20}0$	2.80×10^{20}	2.95×10^{20}	2.19×10^{20}	2.33×10^{20}
NR (sej)	5.58×10^{16}	5.58×10^{16}	5.58×10^{16}	5.58×10^{16}	5.58×10^{16}	5.58×10^{16}	5.58×10^{16}	5.58×10^{16}	5.58×10^{16}	5.58×10^{16}
NP (sej)	3.53×10^{19}	4.57×10^{19}	2.08×10^{20}	2.41×10^{20}	2.62×10^{20}	3.28×10^{20}	3.74×10^{20}	4.35×10^{20}	4.00×10^{20}	4.82×10^{20}
RP (sej)	1.61×10^{20}	1.34×10^{20}	1.51×10^{20}	9.20×10^{19}	1.23×10^{20}	2.91×10^{20}	7.09×10^{19}	6.04×10^{19}	1.00×10^{20}	1.00×10^{20}
U (sej)	4.89×10^{20}	3.97×10^{20}	6.46×10^{20}	6.72×10^{20}	6.63×10^{20}	8.93×10^{20}	7.25×10^{20}	7.91×10^{20}	7.19×10^{20}	8.16×10^{20}
Indices										
RIR	0.928	0.885	0.678	0.641	0.604	0.633	0.484	0.449	0.444	0.409
ESR	0.599	0.548	0.445	0.505	0.419	0.306	0.386	0.373	0.305	0.286
EIR	0.669	0.826	1.248	0.982	1.388	2.265	1.590	1.680	2.277	2.496
ED (sej/m^2)	8.69×10^{11}	7.06×10^{11}	1.15×10^{12}	1.19×10^{12}	1.18×10^{12}	1.59×10^{12}	1.29×10^{12}	1.41×10^{12}	1.28×10^{12}	1.45×10^{12}
EMR (sej/$)	5.07×10^{13}	3.00×10^{13}	9.41×10^{12}	8.39×10^{12}	7.33×10^{12}	8.11×10^{12}	5.75×10^{12}	5.41×10^{12}	5.36×10^{12}	5.04×10^{12}
EYR	2.495	2.211	1.801	2.019	1.720	1.442	1.629	1.595	1.439	1.401
ELR	0.078	0.130	0.474	0.559	0.654	0.581	1.066	1.225	1.251	1.447

Table 5. Indices for Wuyishan's Tea Industry from 1995 to 2004

Index	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Flows										
RR (sej)	2.57×10^{19}	1.76×10^{19}	3.23×10^{19}	4.14×10^{19}	3.04×10^{19}	2.92×10^{19}	3.07×10^{19}	3.66×10^{19}	2.22×10^{19}	2.57×10^{19}
NR (sej)	9.24×10^{15}	7.22×10^{15}	8.10×10^{15}	8.07×10^{15}	8.08×10^{15}	7.96×10^{15}	8.06×10^{15}	8.81×10^{15}	8.99×10^{15}	9.24×10^{15}
NP (sej)	7.20×10^{19}	4.51×10^{19}	5.35×10^{19}	6.16×10^{19}	$5.20\times10^{19}9$	4.53×10^{19}	4.97×10^{19}	6.75×10^{19}	7.04×10^{19}	7.20×10^{19}
RP (sej)	4.55×10^{18}	3.63×10^{18}	4.27×10^{18}	3.80×10^{18}	3.64×10^{18}	3.85×10^{18}	3.94×10^{18}	5.25×10^{18}	4.87×10^{18}	4.55×10^{18}
U (sej)	1.02×10^{20}	6.63×10^{19}	9.01×10^{19}	1.07×10^{20}	8.60×10^{19}	7.84×10^{19}	8.44×10^{19}	1.09×10^{20}	9.75×10^{19}	1.02×10^{20}
Indices										
RIR	0.296	0.320	0.406	0.423	0.396	0.422	0.411	0.383	0.278	0.296
ESR	0.252	0.265	0.359	0.388	0.354	0.373	0.364	0.335	0.228	0.252
EIR	2.974	2.768	1.789	1.579	1.826	1.683	1.745	1.988	3.381	2.974
ED (sej/m^2)	1.65×10^{12}	1.37×10^{12}	1.66×10^{12}	1.97×10^{12}	1.59×10^{12}	1.47×10^{12}	1.56×10^{12}	1.85×10^{12}	1.61×10^{12}	1.65×10^{12}
EMR (sej/$)	1.83×10^{13}	9.27×10^{12}	9.54×10^{12}	9.12×10^{12}	6.79×10^{12}	5.49×10^{12}	5.63×10^{12}	6.54×10^{12}	6.19×10^{12}	4.52×10^{12}
EYR	1.336	1.361	1.559	1.633	1.548	1.594	1.573	1.503	1.296	1.336
ELR	2.378	2.124	1.464	1.363	1.525	1.371	1.434	1.614	2.595	2.378

Table 6. Indices for Wuyishan's Bamboo Industry from 1995 to 2004

Index	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Flows										
RR (sej)	1.14×10^{19}	9.21×10^{18}	2.06×10^{19}	2.67×10^{19}	2.07×10^{19}	2.78×10^{19}	2.98×10^{19}	4.38×10^{19}	2.85×10^{19}	2.08×10^{19}
NR (sej)	2.75×10^{21}	3.73×10^{21}	5.10×10^{21}	5.13×10^{21}	5.42×10^{21}	7.47×10^{21}	7.72×10^{21}	1.04×10^{21}	1.14×10^{21}	7.38×10^{21}
NP (sej)	3.27×10^{17}	4.44×10^{17}	6.07×10^{17}	6.10×10^{17}	6.45×10^{17}	8.88×10^{17}	9.18×10^{17}	1.24×10^{18}	1.35×10^{18}	8.78×10^{17}
RP (sej)	8.26×10^{16}	1.09×10^{17}	1.44×10^{17}	1.40×10^{17}	1.44×10^{17}	1.92×10^{17}	1.93×10^{17}	2.54×10^{17}	2.70×10^{17}	1.71×10^{17}
U (sej)	2.76×10^{21}	3.74×10^{21}	5.12×10^{21}	5.16×10^{21}	5.45×10^{21}	7.50×10^{21}	7.75×10^{21}	1.05×10^{22}	1.14×10^{22}	7.40×10^{21}
Indices										
RIR	0.004	0.002	0.004	0.005	0.004	0.004	0.004	0.004	0.003	0.003
ESR	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
EIR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ED (sej/m^2)	1.48×10^{14}	1.47×10^{14}	1.48×10^{14}	1.48×10^{14}	1.48×10^{14}	1.48×10^{14}	1.48×10^{14}	1.48×10^{14}	1.47×10^{14}	1.47×10^{14}
EMR (sej/$)	8.61×10^{14}	1.17×10^{15}	1.11×10^{15}	1.06×10^{15}	1.02×10^{15}	9.75×10^{14}	9.38×10^{14}	9.05×10^{14}	8.71×10^{14}	8.42×10^{14}
EYR	6738.621	6771.306	6823.797	6871.545	6900.001	6935.447	6970.899	7006.205	7025.791	7058.085
ELR	238.702	400.751	246.040	191.460	260.353	267.167	257.368	236.553	395.362	351.701

4.2.2. Emergy Self-Support Ratio (ESR)

Tables 4 to 6 show that the *ESR* of the bamboo industry equals one to three decimal places of precision. That is, the bamboo industry is almost a self-sustaining industry and requires little external input. The tourism industry requires considerably more external inputs, and became progressively less self-sustaining over time, with *ESR* decreasing from 0.6 to 0.3; the *ESR* of the tea industry remained relatively con- stant at around 0.3. Both the tourism industry and the tea in- dustry therefore need considerable external support. For the tea industry, the external support is always much greater than the support provided by the local environment. For the tou- rism industry, the environment's contribution changed from being the primary source of support to a secondary source.

4.2.3. Emergy Investment Ratio (EIR)

Tables 4 to 6 show that the *EIR* of the tourism industry was higher than one for the last five years of the study period, whereas those of the tea industry were higher than one throughout the study period. This means that the economic cost was greater than the free investment provided from the environment. The *EIR* of tourism increased greatly during the study period, indicating that tourism has developed rapidly and may have matured. The *EIR* of the tea industry decreased sharply in 1997 and remained relatively low until 2002, then returned to its 1995 level by 2004. This indicates that the tea industry endured a recession from 1997 to 2002 and that the government-induced changes in the industry led to increased investment. The bamboo industry is more dependent on raw materials than on their transformation, so its *EIR* equaled 0 to three decimal places of precision. The low cost makes the bamboo industry economically competitive, but the industry remains undeveloped and over-reliant on nature.

4.2.4. Emergy Density (ED)

Tables 4 to 6 show that the *ED* of bamboo industry was roughly two orders of magnitude higher than those of the tourism and tea industries; it remained constant at about 1.48 × 10^{14} sej/m^2 throughout the study period. The *ED* of the tourism and tea industries were similar throughout most of the study period. The *ED* of tourism increased from 8.69 × 10^{11} sej/m^2 in 1995 to 14.5 × 10^{11} sej/m^2 in 2004, with slight fluctuations. The *ED* of the tea industry fluctuated only slightly. These results indicate that the bamboo industry produces more significant environmental impacts than the tourism and tea industries, and these impacts resulted mainly from the biodiversity loss and topsoil loss caused by the cultivation of pure bamboo forests.

4.2.5. Emergy Money Ratio (EMR)

Tables 4 to 6 show that the *EMR*s of the tourism and tea industries decreased, but at different rates. The *EMR* of tourism decreased from 5.07 × 10^{13} to 0.50 × 10^{13} sej·\$$^{-1}$ and that of tea industry decreased from 1.83 × 10^{13} to 0.45 × 10^{13} sej·\$$^{-1}$, whereas that of bamboo industry remained nearly unchanged. The *EMR* of bamboo industry was roughly two orders of magnitude higher than those of the tourism or tea industry. This suggests that the economic benefits of the bamboo industry require more emergy inputs and that this is a potential barrier to the long-term development of the local economy. The *EMRs* of the tourism and tea industries have become similar since 1997, and both stabilized around 1997, which means that the emergy-use efficiency of the two Industries has stopped improving.

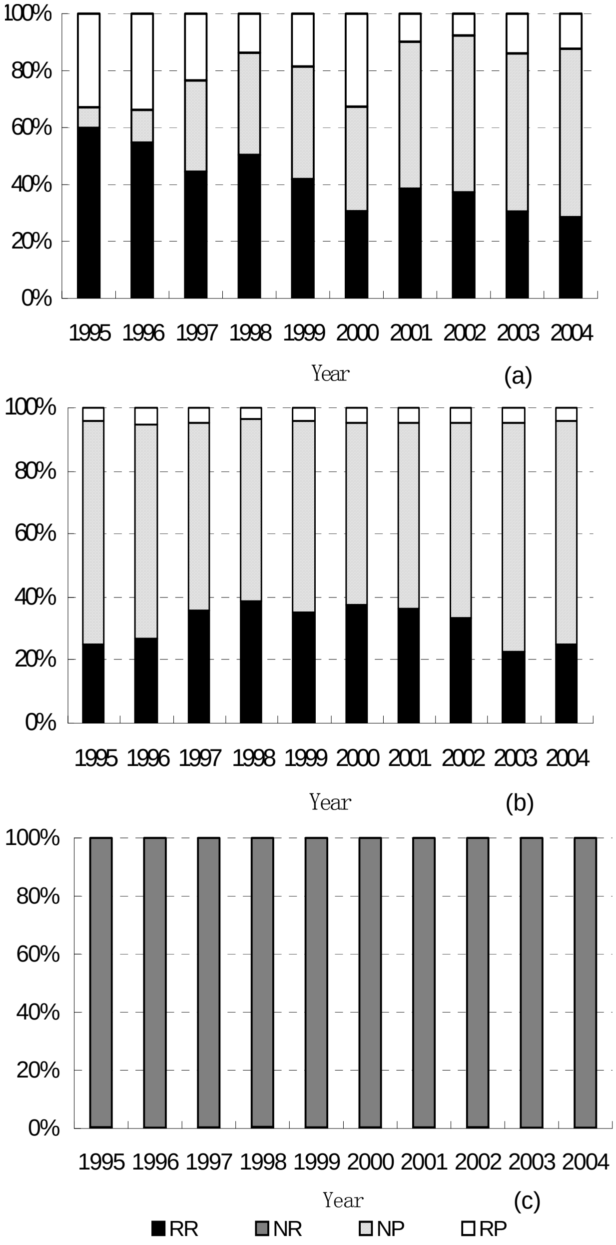

Figure 7. The emergy structures of Wuyishan's main industries from 1995 to 2004. (a) Tourism Industry; (b) Tea Industry; (c) Bamboo Industry.

4.2.6. Emergy Yield Ratio (EYR)

Tables 4 to 6 show that the bamboo industry's *EYR* is much higher (by roughly three orders of magnitude) than those of the tourism and tea industries, and has been increasing steadily. This means that the bamboo industry benefits from a relatively smaller investment, and depends almost completely on the natural environment. The *EYR* of tourism decreased from 2.5 to 1.4 during the study period, with a small oscillation, suggesting that the increase in purchased inputs has not resulted in a corresponding yield increase. The tea industry's *EYR* was the smallest (less than 1.6 throughout the study period), and it remained relatively stable, indicating that Wuyishan's tea production and market are mature and that there is a relatively stable correlation between supply and demand.

4.2.7. Environmental Loading Ratio (ELR)

Tables 4 to 6 show that the bamboo industry's *ELR* was the highest (by as much as two orders of magnitude). It indicates that the bamboo industry uses more non-renewable resources than renewable resources. The *ELR* of tourism increased from 0.08 in 1995 to 1.45 in 2004, suggesting that the industry consumes more non-renewable resources now while it consumed more renewable resources in the past. The tea industry's *ELR* was greater than 1 throughout the study period, indicating that the industry has consistently used more non-renewable than renewable resources. Because the tea industry's *ELR* decreased between 1995 and 2000, then increased, its use of non-renewable resources has increased more than its use of renewable resources.

5. Discussion

Of the seven analyzed indices, *ED* and *EMR* both represent the emergy use intensity from, respectively, the perspectives of space and economic benefit. *EYR* represents the process efficiency, which reflects the efficiency of the purchased inputs. *RIR*, *ESR*, *EIR*, and *ELR* all reflect the emergy use structure and the resulting environmental load. Based on its current state of development, the bamboo industry is more environmentally damaging than the other two industries in terms of its emergy-use intensity and its environmental load, but has a better process efficiency. The tourism and tea industries were similar in terms of these indices, but tourism had the lowest environmental load, which is the most important factor in Wuyishan City. Based on the different characteristics of the three industries, different approaches will need to be taken to achieve sustainable economic development.

The tourism industry is relatively environmentally friendly in Wuyishan. It showed a similar temporal trend in all the indices, indicating that tourism developed continuously during the study period. Considering the relationships among the indices, the increase in tourism's outputs mainly resulted from its increase of purchased resources, such as building infrastructure and maintenance operations. However, the marginal benefit of these investments has gradually decreased. Considering the reduction of marginal benefits from purchased inputs, the development mode should be changed towards a more ecologically sustainable mode. Because of its relatively low environmental impact, the tourism industry should be promoted so that it retains its dominant economic status.

The tea industry has remained relatively stable during the study period, although the government's policy to close, merge, or transform the smallest tea factories has increased the industry's reliance on purchased resources in recent years. This result is consistent with the tea industry's status as a traditional and mature industry. It is also an industry that provides a high level of economic benefit, but at the expense of high ecological costs. The topsoil loss that currently occurs in tea plantations should be eliminated to ensure that development of the tea industry is sustainable. Because the current rate of topsoil loss in southern hilly areas of China concerns researchers (Zhou et al., 2003; Lv et al., 2004; Chen, 2009; Lv, 2009), solutions that can reduce soil loss, such as interplanting tea with mulberry or rice crops, should be applied in Wuyishan.

The bamboo industry differs significantly from the other two industries. It depends excessively on local natural resources, and especially on non-renewable resources, but requires little in the way of artificial inputs. Its emergy-use intensity is therefore high. Local managers should control the bamboo industry so that it does not encroach on sensitive areas where rare species would be endangered. Intercropping with broad-leaved forests should be investigated to determine whether it is a viable option for preserving biodiversity without decreasing revenues from the industry. Many studies in surrounding areas with a similar ecological environment, such as in the southern area of Zhejiang Province and the northern area of Fujian Province, have demonstrated that such intercropping can generate improved returns compared with pure bamboo forests in terms of timber quality (Wu et al., 2007), overall productivity (Yan, 2008), biomass (Chen, 2007), biodiversity (Gao and Fu, 2005; Zhang et al., 2007a), soil fertility (Zhang et al., 2010a), and water interception capacity (Zhang et al., 2010b). In addition, the bamboo industry has considerable potential for future development to improve the economic benefits through appropriate investment. For example, the government should encourage the production of manufactured (value-added) bamboo products rather than relying solely on sales of the raw materials produced by harvesting.

6. Conclusions

Emergy analysis can be used to quantify the inputs from an ecosystem and an industry's impact on its environment. In this study, we used dynamic comparisons to reveal changes in seven synthetic emergy indicators for Wuyishan's tourism, tea, and bamboo industries. In the city of Wuyishan, conflicts between the industrial and economic development and the environmental protection have become increasingly severe since 1995. Several conclusions could be drawn from our analysis:

(1) From 1995 to 2004, tourism developed continuously, mainly as a result of increases in its purchased resources. The tea industry remained relatively stable, which is consistent with its status as a mature traditional industry. The bamboo Industry had the highest emergy-use intensity and process efficiency, but produced the highest environmental load. It depends excessively on the consumption of non-renewable resources and has considerable development potential.

(2) Tourism is currently Wuyishan's most environmentally friendly industry, although its development mode should be

improved to focus on sustainability. The tea industry is stable, but topsoil loss from tea plantations must be stopped quickly to ensure future sustainable development of the industry. The bamboo industry's development should be controlled so that it will not adversely affect sensitive areas with high biodiversity. Solutions such as intercropping and the production of more processed (value-added) goods should be investigated.

We analyzed Wuyishan's three main industries independently in this study. However, complicated correlations may exist among the industries, leading to uncertainties in the interpretation of the results. Future research efforts would emphasize identification of correlations among the three industries and the impacts of these correlations for decision-makers. Besides, the researchers could apply a multi-criterion decision analysis to achieve a more comprehensive result and comparison among more industries.

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