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Article

Emergy Synthesis and Regional Sustainability Assessment: Case Study of Pan-Pearl River Delta in China

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Abstract: In this paper, emergy analysis is used in association with the ternary diagrams and geographic information system (GIS) tools to improve the evaluation of sustainability for the Pan-Pearl River Delta (PPRD) region. Emergy accounting of PPRD is estimated, and various emergy-based indicators are reported. Ternary diagrams are drawn to provide a graphical representation of the emergy accounting data. Finally, the GIS tools are employed to assist in the emergy-based spatial analysis, and emergy density based on flat land area is mapped to reflect the intensity of emergy use in human activity areas. Results show the following: (1) the current development path of the PPRD region, with the value of emergy sustainability index (ESI = 0.227) significantly lower than one, is unsustainable in the long run; (2) Guangdong has the lowest ESI value (0.071), and the ESI values of Fujian, Guangxi, Hunan and Jiangxi are lower than 0.5, indicating that the economy in these provinces overly relies on non-renewable and imported resources; (3) Guizhou has a high emergy yield rate and is thus the main energy supplier in PPRD; and (4) among the nine provinces in PPRD, only Hainan has an ESI value (2.145) higher than one.

Keywords: emergy synthesis; ternary diagram; regional sustainability assessment; pan-pearl river delta

1. Introduction

A region is an open system whose development depends on the interaction between its subsystems and its reciprocity with an external system. Interaction and reciprocity are maintained through the flow of resources, including energy, matter, human activities, money and information. Regional sustainable development is dependent not only on the contribution from various goods and services, as traditionally valued, but also on various environmental resource flows that have been discounted or even completely ignored [1].

Emergy synthesis, which is based on biology energetics and general systems theory and systems ecology [2], allows us to quantify these flows and provides a comprehensive balance to evaluate the sustainability of a region [3]. By means of emergy-based indices, Emergy synthesis has been utilized to evaluate sustainability in numerous research fields, such as agriculture management [4,5], industrial processes [6] and urban metabolism [7,8].

In some theoretical studies and discussions [3,9–16], emergy synthesis was compared with other sustainability metrics, such as ecological footprint, well-being index and surplus biocapacity measure. Emergy synthesis seems to be a more adequate and transparent metric for measuring the real effect of human activity on a territory and the combined expressions of human behavior that affect the external environment in different ways [17–19]. Emergy synthesis of territorial systems has been performed all over the world [1,3,20–37].

Among the above-mentioned studies, two important tools—ternary diagram and geographic information system—can be integrated into emergy evaluation to improve the framework of regional studies. The ternary diagram is introduced by Giannetti *et al.* [13] into emergy analysis. It can be employed to improve the decision-making process, because it simultaneously provides theoretical support and easy handling [38]. The diagram is useful especially when employed in the study of several productive processes [39,40]. Second is the geographic information system (GIS). In some cases, geographic information system (GIS) tools are incorporated into emergy synthesis to represent the spatial distribution of energy consumptions [3,39,41].

In this paper, emergy analysis was used in association with the GIS tools and ternary diagrams to improve the evaluation of sustainability in Pan-Pearl River Delta (PPRD) and its provinces.

2. Methods

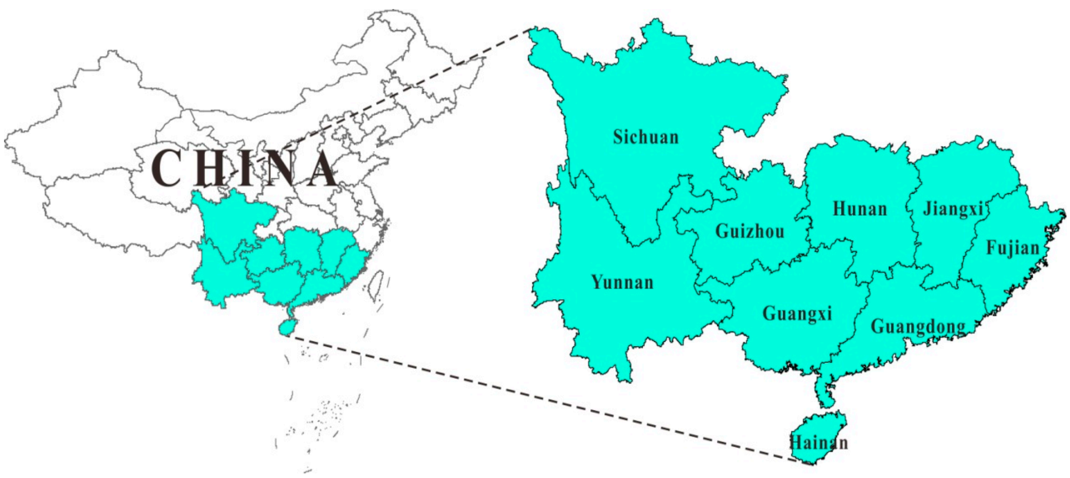
2.1. Study Area

Pan-Pearl River Delta (PPRD), as a regional cooperation system, was officially launched after the signing of the “Pan-Pearl River Delta Cooperation Framework Agreement” in Guangzhou on 3 June 2004 [42]. The PPRD region (97°21′–120°40′E, 18°10′–34°19′N) covers a land area of 2,010,000 km^2

and comprises nine provinces, namely, Guangdong, Fujian, Jiangxi, Hunan, Guangxi, Hainan, Sichuan, Guizhou and Yunnan, as well as the Hong Kong and Macao Special Administrative Regions.

In view of data availability and practical circumstances, this study focus on nine provinces (see Figure 1) in the mainland. These provinces account for 20% of the total area of China and represent one-third of the country's population. In addition, the PPRD region registers more than 35% of China's total economic output.

Figure 1. Location of the Pan-Pearl River Delta (PPRD) region.



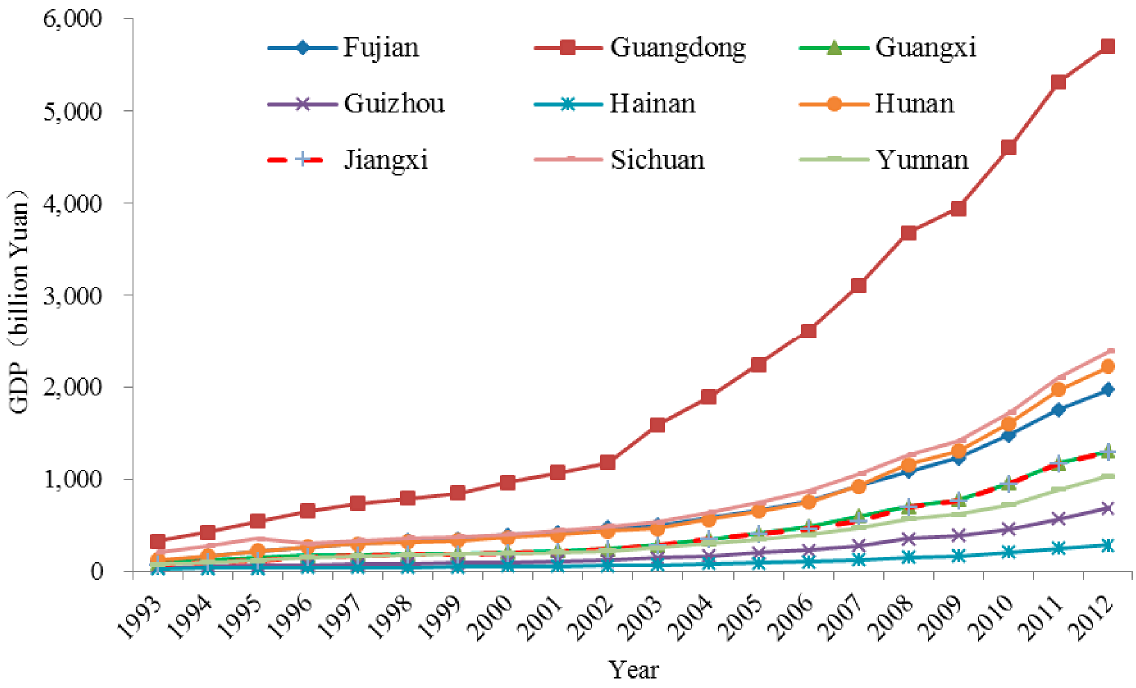
The PPRD can be seen as the extension of the Pearl River Delta (PRD). The latter is centered on Guangdong province. Transformed from a rural backwater into the world's workshop through Deng Xiaoping's economic reforms and the proximity of Hong Kong's capital, technology and business skills, the PRD—China's richest—is the world's largest supplier of everything, from televisions to toys. However, worsening pollution, infrastructure and power bottlenecks, severe labor shortages and rising wage costs are combining to take the edge off that success. The PRD is starting to lose investors to another of China's economic and political heavyweights—Shanghai and the Yangtze River Delta (YRD), which enjoys better access to China's huge domestic market. This has prompted the region to come up with a typically Chinese solution: to grow their way out of the problem by extending the PRD [43].

The "Pan-Pearl River Delta Region" concept was proposed to lay a firm foundation for future co-operation in the area of infrastructure, industries and investment, commerce and trade, tourism, agriculture, labor, education and culture, information system, environmental protection and health and quarantine [44]. As many provinces and units are at different levels of development, with diverse socio-economic makeup, there is a goodness-of-fit for them to co-operate for their mutual advantage [45].

In economic development, although nine provinces all exhibit increasing economic trends, they exhibit different speeds of economic development (see Figure 2). As shown in Figure 2, economic disparity among the nine provinces has increased in the past 20 years. Several studies show that the economic disparities will continue to rise in future years [46].

The burgeoning economic aggregate and rising economic difference will inevitably increase the environmental loads and decrease regional sustainability. Thus, the regional sustainability evaluation of PPRD based on the interaction between human activities and the ecosystem is necessary to improve the decision-making and policy formulation of this region.

Figure 2. Gross domestic product of nine provinces in the PPRD region.



2.2. Emergy Synthesis

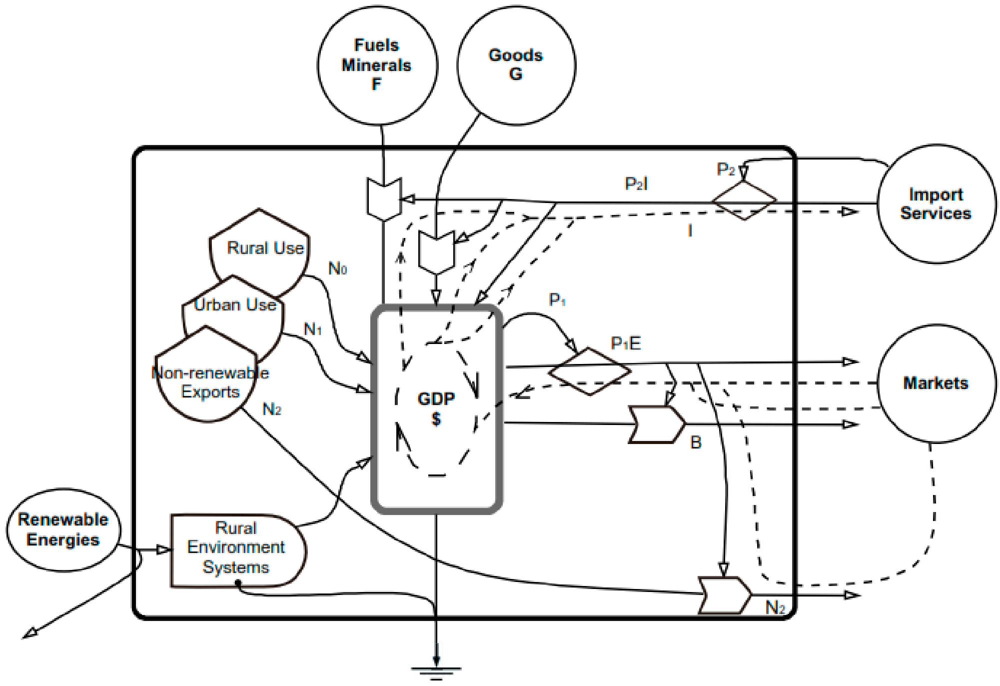
Emergy synthesis, introduced by Odum [47], is a thermodynamic-based methodology. It provides a series of useful and easily accessible indices to evaluate the sustainability of a region. The first step involves the drawing of a system diagram. Then, tables of the actual flows are constructed from the diagrams. Finally, several emergy-based indicators can be calculated relating to various resource types to assess a process performance.

Figure 3 shows an aggregated system diagram for PPRD in 2011. The diagram was developed based on the emergy and dollar flows across system boundaries, the interaction of renewable and non-renewable resources within the system and the exchanges of emergy and dollars that drive the system's economy. The energy system language uses symbols to represent the internal active network of a system. Circles stand for external energy sources, bullets for producers, hexagons for consumers, rectangular arrowheads for interactions and diamonds for economic exchange [34].

In Figure 3, the rectangle with a heavy line defines the boundaries of the study system. It covers different flows, including energy, matter, money and information, all of which contribute to the studied system. Resources are categorized based on their origin: either from outside of the system or from within the system. Resources are also classified as either renewable or non-renewable.

Natural resource inputs and renewable resources, R, such as sun, rain and wind, enter the system from the left. Non-renewable resources created within the system boundaries are N_0, N_1 and N_2. N_0 represents rural resources, such as soil and biomass, whose consumption rates within the system are hypothetically more than their regeneration rates. N_1 refers to reserves of fuels and minerals that are renewed over long geologic times. N_2 refers to the flow of resources that pass through the system without significant transformation, such as minerals that are mined and exported abroad without further processing.

Figure 3. Energy system diagram of PPRD in 2011.



Imports to the system are shown on the top and right in Figure 3. Imports include the emergy of fuels and minerals (F), goods (G) and imported service (P_2I). The flow of money is designated by a dashed line and $ in the system diagram. Exports to the market, beneath the imported services, have pathways for fuels, goods and services similar to those discussed for imports. The emergy of goods and non-renewable exports, labeled as B and N_2, respectively, includes the emergy of services required in their process and delivery. Money received from exports and outputs in the markets on the right is represented by dashed lines that add up to the gross domestic product (GDP) of a system. Total emergy use (U) in the system is the sum of all of the inputs ($U = R + N_0 + N_1 + F + G + P_2I$), which reflects the system's annual wealth.

Table 1 shows major emergy flows in PPRD region in the year 2011. It includes the quantities of resources consumed with the corresponding transformity and equivalent amount of energy flows for each resource. Detailed emergy calculations and raw data for emergy flows of PPRD region are provided in Appendix.

We then calculated a series of emergy-based indices (Table 3) based on the flows of energy and products (Table 2). The transformities in this study are relative to the 15.20×10^{24} sej/year planetary emergy baseline [48].

Table 1. Emergy analysis table for the PPRD region in 2011.

No.	Item	Raw data	Unit	Transformity(sej/unit)	Reference	Solar Emergy (E20 sej)
Renewable Resources (R)						
1	Sunlight	1.32×10^{22}	J/year	1.00	[49]	132.30
2	Rain, chemical	1.44×10^{19}	J/year	3.05×10^{4}	[49]	4407.02
3	Rain, geopotential	5.05×10^{18}	J/year	4.70×10^{4}	[49]	2372.65
4	Wind, kinetic energy	5.99×10^{19}	J/year	2.45×10^{3}	[49]	1466.68
5	Waves	3.28×10^{18}	J/year	5.10×10^{4}	[49]	1670.86
6	Tide	6.78×10^{18}	J/year	7.39×10^{4}	[49]	5009.69
7	Earth Cycle	2.91×10^{18}	J/year	5.80×10^{4}	[49]	1688.91
	Total R					8450.53
Nonrenewable Resources From Within Country (N)						
Dispersed Rural Source (N_0)						
8	Hydroelectricity	1.55×10^{18}	J/year	3.22×10^{5}	[47]	4995.65
9	Agriculture Production	8.38×10^{18}	J/year	3.22×10^{5}	[50]	26,985.59
10	Livestock Production	1.31×10^{17}	J/year	3.22×10^{6}	[50]	4206.04
11	Fisheries Production	1.01×10^{17}	J/year	3.22×10^{6}	[50]	3256.14
12	Fuelwood Production	2.14×10^{16}	J/year	2.21×10^{4}	[51]	4.73
13	Forest Extraction	7.61×10^{17}	J/year	2.21×10^{4}	[51]	168.08
14	Soil Losses	4.05×10^{14}	g/year	1.61×10^{9}	[47]	6523.66
15	Topsoil Losses	2.75×10^{17}	J/year	7.40×10^{4}	[52]	203.33
	Total N_0					10,155.94
Concentrated Use (N_1)						
16	Natural Gas	6.85×10^{17}	J/year	5.88×10^{4}	[51]	402.61
17	Oil	9.40×10^{18}	J/year	8.53×10^{4}	[47]	8025.05
18	Coal	1.41×10^{19}	J/year	6.41×10^{4}	[47]	9043.14
19	Minerals	9.43×10^{14}	g/year	1.11×10^{9}	[47]	10,516.74
20	Metals	2.31×10^{14}	g/year	1.03×10^{9}	[47,53]	2380.58
	Total N_1					30,368.12
Imports and Outside Sources (F'):						
Imported Fuels and Minerals (F)						
21	Fuels	2.42×10^{19}	J/year	8.03×10^{4}	[47,51]	19,439.21
22	Metals	3.92×10^{13}	g/year	9.85×10^{9}	[47,53,54]	3857.79
23	Minerals	4.21×10^{11}	g/year	7.41×10^{10}	[47,54]	312.15
	Total F					23,609.15
Imported Goods (G)						
24	Food and ag. products	3.90×10^{17}	J/year	3.22×10^{5}	[50]	1255.82
25	Livestock, meat, fish	1.19×10^{15}	J/year	3.22×10^{6}	[50]	38.24
26	Plastics and rubber	1.55×10^{17}	J/year	1.06×10^{5}	[47]	164.45
27	Chemicals	1.29×10^{13}	g/year	1.48×10^{10}	[55]	1908.78
28	Finished materials	1.89×10^{13}	g/year	2.72×10^{9}	[54,56]	514.07
29	Mach. and trans equip.	3.94×10^{9}	$	2.70×10^{12}	[57]	106.28
	Total G					3987.65

Table 1. *Cont.*

No.	Item	Raw data	Unit	Transformity(sej/unit)	Reference	Solar Emergy (E20 sej)
			Emergy of Services in Imported Goods & Fuels (P_2I)			
30	Service in imports	4.99×10^{11}	$	2.70×10^{12}	[57]	13,479.08
			Exports			
			Exported production (B)			
31	Food and ag. products	2.05×10^{17}	J/year	3.22×10^{5}	[50]	658.61
32	Livestock, meat, fish	1.00×10^{17}	J/year	3.22×10^{6}	[50]	3,235.04
33	Finished materials	7.36×10^{12}	g/year	3.74×10^{9}	[54,56]	275.36
34	Mach. and trans equip.	2.58×10^{11}	$	3.83×10^{12}	this study	9,876.74
35	Plastics & rubber	1.31×10^{17}	J/year	1.06×10^{5}	[47]	139.07
	Total B					14,184.83
			Exported without Use (N_2)			
36	Fuels	5.04×10^{18}	J/year	8.04×10^{4}	[47,51]	4,055.00
37	Metals	5.13×10^{12}	g/year	2.08×10^{10}	[47,53,54]	1,066.26
38	Minerals	5.18×10^{12}	g/year	8.87×10^{9}	[47,54]	458.97
39	Chemicals	6.87×10^{11}	g/year	1.48×10^{10}	[55]	101.70
	Total N_2					5,681.93
			Emergy Value of Service Exports (P_1E)			
40	Service in exports	6.25×10^{11}	$	3.83×10^{12}	this study	23,927.55

Table 2. Summary of emergy flows in PPRD and its provinces.

	Item/Units	Guang-dong	Fu-jian	Jiang-xi	Hu-nan	Gui-zhou	Guang-xi	Hain-an	Yun-nan	Si-chuan	PPRD
R	Renewable emergy/10^{23} sej/year	1.37	0.86	0.32	0.33	0.32	0.63	1.68	1.26	1.67	8.45
N_0	Dispersed rural source/10^{23} sej/year	1.69	1.02	1.07	1.45	0.72	1.27	0.34	1.03	1.57	10.16
N_1	Concentrated use (fuels, *etc.*)/ 10^{23} sej/year	3.36	1.86	2.06	3.67	7.24	2.04	0.37	3.99	5.78	30.37
N_2	Fuels exported without use/ 10^{23} sej/year	1.26	0.60	0.49	0.53	0.72	0.81	0.52	0.33	0.41	5.68
F	Imported minerals/10^{23} sej/year	8.36	2.66	1.67	2.18	0.43	3.19	1.05	2.42	1.64	23.61
G	Imported goods/ 10^{23} sej/year	1.68	0.98	0.11	0.13	0.01	0.27	0.08	0.28	0.45	3.99
P_2I	Imported services/10^{23} sej/year	10.30	1.37	0.26	0.25	0.05	0.29	0.28	0.18	0.51	13.48
I	Dollars paid for imports/10^{10} $/year	38.15	5.07	0.96	0.91	0.19	1.09	1.02	0.66	1.87	49.92
B	Exported productions/ 10^{23} sej/year	9.02	2.55	4.95	1.41	1.04	5.97	1.41	2.51	8.86	14.18

Table 2. *Cont.*

	Item/Units	Guang-dong	Fu-jian	Jiang-xi	Hu-nan	Gui-zhou	Guang-xi	Hain-an	Yun-nan	Si-chuan	PPRD
P_1E	Exported services, total/10^{23} sej/year	17.28	2.99	0.66	0.26	0.30	0.53	0.25	0.63	1.04	23.93
E	Dollars paid for all exports/10^{10} \$/year	53.18	9.28	2.19	0.99	0.30	1.25	0.25	0.95	2.90	71.29
P_1	PPRD EMR/ 10^{12} sej/\$	3.25	3.22	3.03	2.63	9.95	4.23	9.70	6.65	3.57	3.83
P_2	World EMR/ 10^{12} sej/\$	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70

Table 3. The emergy indicators and indices for PPRD and its provinces. EIR, emergy investment ratio; EYR, emergy yield ratio; ESI, emergy sustainability index; ELR, environment loading ratio.

Index name/Units/Calculation	Guang-dong	Fu-jian	Jiang-xi	Hu-nan	Gui-zhou	Guang-xi	Hai-nan	Yun-nan	Si-chuan	PPRD
Non-renewable emergy/ 10^{23} sej/year/$N = N_0 + N_1$	5.05	2.89	3.13	5.12	7.96	3.30	0.70	5.02	7.35	40.52
Imported emergy/ 10^{23} sej/year/$F' = F + G + P_2I$	20.35	5.01	2.04	2.56	0.50	3.75	1.41	2.88	2.60	41.08
Total emergy used/10^{23} sej/year/ $U = R + N + F + G + P_2I$	26.76	8.76	5.49	8.01	8.78	7.68	3.79	9.15	11.62	90.05
Exported emergy/10^{23} sej/year/ N_2 + P1E + B	27.55	6.15	1.65	0.94	1.12	1.94	0.91	1.21	2.33	43.79
Ratio of exports to imports/ $(N_2 + P_1E + B)/(F + G + P_2I)$	1.35	1.23	0.81	0.37	2.25	0.52	0.65	0.42	0.90	1.07
Renewable percentage/%/R/U	5.11	9.84	5.80	4.16	3.67	8.24	44.34	13.77	14.40	9.38
Indigenous percentage/%/ (R + N)/U	23.97	42.80	62.89	68.08	94.35	51.25	62.87	68.56	77.66	54.39
Electricity percentage/%/Electricity/U	1.69	4.44	1.98	7.81	5.51	7.38	0.45	15.01	16.01	6.53
Emergy-to-money ratio/ 10^{12} sej/\$/U/GDP	3.25	3.22	3.03	2.63	9.95	4.23	9.70	6.65	3.57	3.83
Emergy density/ 10^{12} sej/year km^2/U/Area	14.88	7.22	3.29	3.78	4.98	3.23	10.70	2.32	2.40	4.48
Emergy per person/ 10^{16} sej capita/U/Population	2.55	2.36	1.22	1.12	2.53	1.48	4.32	1.98	1.44	1.87
Emergy investment ratio/ EIR = $(F + G + P_2I)/(R + N)$	3.17	1.34	0.59	0.47	0.06	0.95	0.59	0.46	0.29	0.84
Electricity percentage/%/Electricity/U	1.69	4.44	1.98	7.81	5.51	7.38	0.45	15.01	16.01	6.53
Emergy-to-money ratio/10^{12} sej/\$/U/GDP	3.25	3.22	3.03	2.63	9.95	4.23	9.70	6.65	3.57	3.83

Table 3. *Cont.*

Index name/Units/Calculation	Guang-dong	Fu-jian	Jiang-xi	Hu-nan	Gui-zhou	Guang-xi	Hai-nan	Yun-nan	Si-chuan	PPRD
Emergy density/ 10^{12} sej/year km^2/U/Area	14.88	7.22	3.29	3.78	4.98	3.23	10.70	2.32	2.40	4.48
Emergy per person/ 10^{16} sej capita/U/Population	2.55	2.36	1.22	1.12	2.53	1.48	4.32	1.98	1.44	1.87
Emergy investment ratio/ EIR = (F + G + P_2I)/(R + N)	3.17	1.34	0.59	0.47	0.06	0.95	0.59	0.46	0.29	0.84
Emergy yield ratio/ EYR = U/(F + G + P_2I)	1.32	1.75	2.70	3.13	17.69	2.05	2.69	3.18	4.48	2.19
Environment loading ratio/ ELR = N + F + G + P_2I)/R	18.57	9.16	16.25	23.03	26.26	11.13	1.26	6.26	5.94	9.66
Emergy sustainability index/ESI = EYR/ELR	0.071	0.191	0.166	0.136	0.674	0.184	2.145	0.508	0.753	0.227

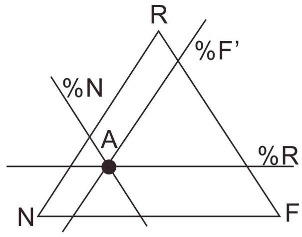
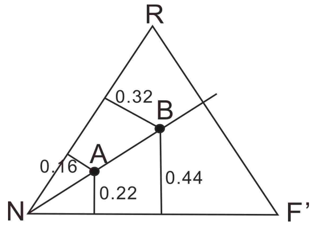
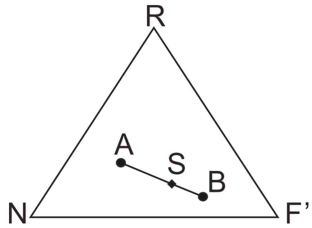
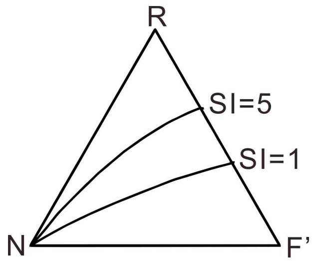
Raw input data for PPRD and its provinces in the region are gathered from the most recent data available in reliable databases, such as the China Energy Statistical Yearbook 2012 [58], the China Forestry Statistical Yearbook 2011 [59] and the China Trade and External Economic Statistical Yearbook 2012 [60].

2.3. Emergetic Ternary Diagrams

The concept of ternary diagrams was proposed by Gibbs and Roozeboom for the analysis of mixed components and introduced into emergy synthesis by Giannetti *et al.* [13]. The representation of emergy values on the ternary diagram allows prompt visualization of the results and facilitates comparison among provinces in PPRD.

An emergetic ternary diagram consists of three components: R, N and F' (here, F' refers to the total imported emergy and equals the sum of F, G and P_2I). The percentages of the three components usually add up to 100, or three fractions, or the proportions add to one. These components can be represented in an equilateral triangle; each corner represents an element and each side a binary system. Ternary combinations are represented by points within the triangle, the relative proportions of the elements being provided by the lengths of the perpendiculars from the given point to the side of the triangle opposite to the appropriate elements. Thus, the "composition" of any point plotted on a ternary diagram can be determined by reading from zero along the basal line at the bottom of the diagram to 100% at the vertex of the triangle. Table 4 illustrates the four important properties of ternary diagrams using auxiliary lines.

Table 4. Properties of emergetic ternary diagrams.

Properties	Description	Illustration
Resource flow lines	Ternary combinations are represented by points within the triangle, the relative proportions of the elements being given by the lengths of the perpendiculars from the given point to the side of the triangle opposite the appropriate element. These lines are parallel to the triangle sides and are very useful for comparing the use of resource by-products or processes.	
Sensitivity lines	Any point along the straight line joining an apex to a point represents a change in the quantity of the flux associated with the apex. Any point along the line represents a condition in which the other two fluxes maintain in the same initial proportion. For example, the system illustrated on the right is progressively poorer in N, as it passes from A to B, but R and F maintain at the same initial proportion.	
Symergy point	When two different ternary compositions, represented by points A and B within the triangle, are mixed, the resulting composition will be represented by a point, S, called here the ''symergy'' point, which lies at some point on the segment, AB.	
Sustainability lines	The graphic tool permits one to draw lines indicating constant values of the sustainability index. The sustainability lines depart from the N apex in the direction of the RF side allowing the division of the triangle into sustainability areas, which are very useful to identify and compare the sustainability of products and processes.	

3. Results and Discussion

Figure 4 shows the categories of resource consumption in terms of emergy flows. In PPRD, most of the total emergy used is caused by high quantities of non-renewable resources that consist of imported fuels and minerals (F) and relatively higher urban concentrated use (N_1). The ratio of emergy use between rural and urban areas is 1:1.64. A relevant portion of emergy flows depends on imported services (P_1E).

Figure 5 shows the resource consumption for the provinces in PPRD region. The consumptions in these provinces are not homogeneous, showing different conditions in different areas. Guangdong Province achieves the highest imports emergy value ($F' = 2.03 \times 10^{24}$) in PPRD. Sichuan ($N = 7.35 \times 10^{23}$) and Guizhou ($N = 7.96 \times 10^{23}$) show high values of local non-renewable resource use, especially because of the presence of mining and industrial activities. Hainan province shows a high value of renewable resource flow ($R = 1.68 \times 10^{23}$), as a result of its expansive continental shelf and long coastline.

Figure 4. Emergy flows of resource consumption in the PPRD region

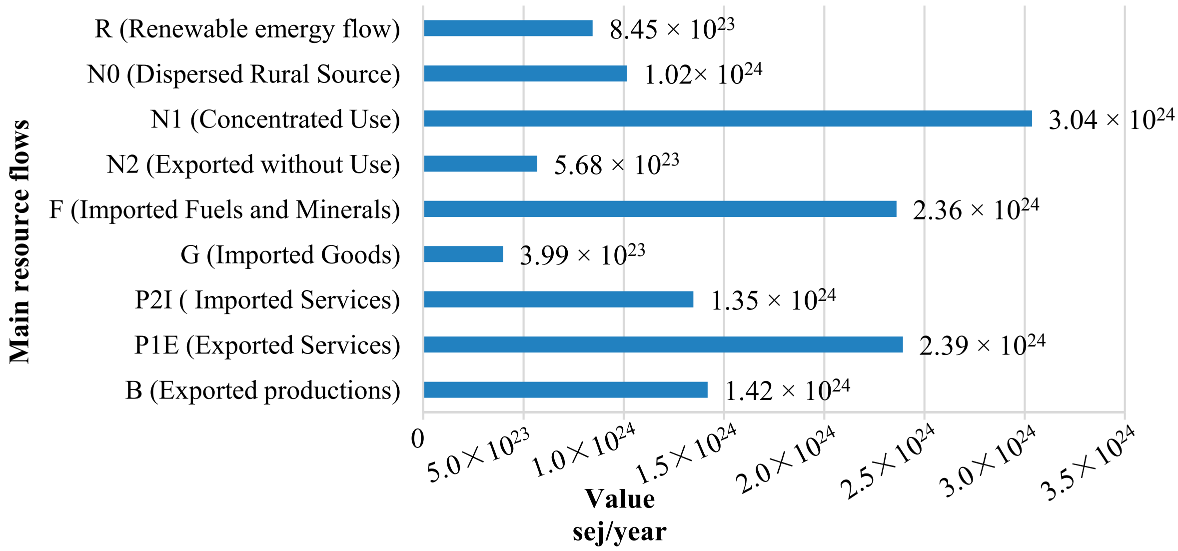
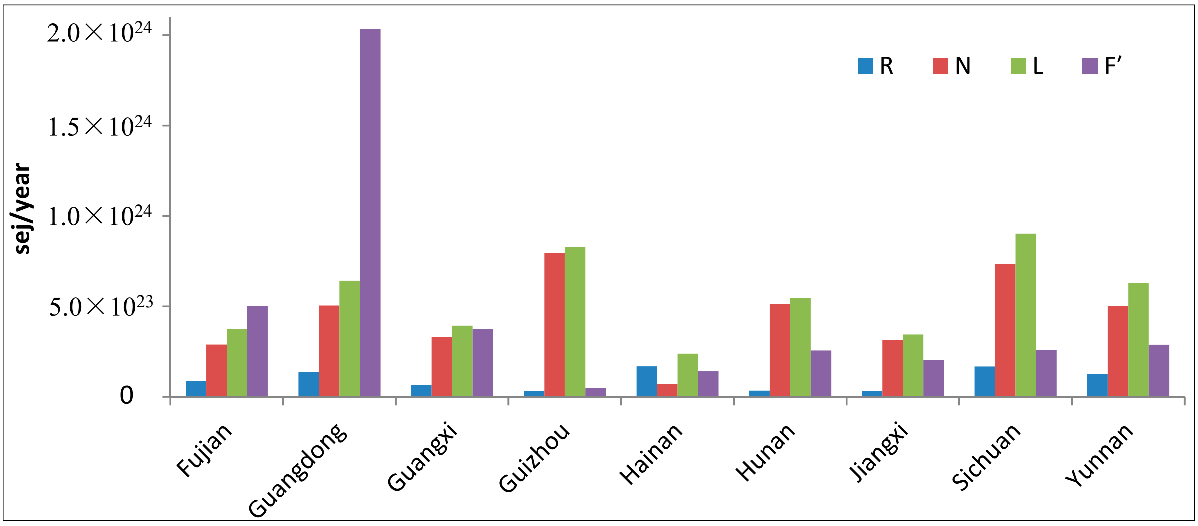


Figure 5. Emergy flows classified as renewable (R), non-renewable (N), local (L) and total imports (F') for the provinces in Pan-Pearl River Delta in 2011.



3.1. Emergy Indices

3.1.1. Emergy Investment Ratio (EIR)

The emergy investment ratio (EIR) is the ratio of purchased inputs to local resources. It shows the relation between the emergy of the economic inputs and those provided by the environment, renewable or not. The EIR values of Guangxi, Guizhou, Hainan, Hunan, Jiangxi, Sichuan and Yunnan are less than one, indicating that these provinces rely more on locally available resources than on purchased inputs. Meanwhile, the EIR values of Fujian (1.34) and Guangdong (3.17) are greater than one, indicating that imports are necessary in these provinces.

3.1.2. Emergy Yield Ratio (EYR)

The emergy yield ratio (EYR) is the total emergy used (U) divided by the total emergy invested. EYR represents the emergetic return on economic investment. The higher the EYR value, the lower the system's dependence on economic investment. Guizhou (17.69) and Sichuan (4.48) show high values of EYR, which indicates the importance of these provinces, especially Guizhou, in providing energy, mainly in the form of thermal power, to the PPRD and even to the economy of China. This high value results from the use of non-renewable energy in the two provinces.

3.1.3. Environment Loading Ratio (ELR)

ELR is the ratio of non-renewable and imported emergy use to renewable emergy use. ELR is an indicator of the stress on the local environment caused by the production activity. The ELR value for the PPRD region and its provinces, except for Hainan (ELR = 1.26), is higher than five. This high ratio indicates that the equilibrium (in 2011) is broken between the availability of natural renewable resources and the exploitation of non-renewable resources (such as fossil fuels) in the PPRD. Guizhou (ELR = 26.26) and Hunan (ELR = 23.03) have ELR values higher than 20, indicating the over-exploitation of non-renewable resources. By contrast, the ELR value of Hainan is low, which means that the location has very low influence in terms of resource use and extraction and can be considered as a location of natural capital storage.

3.1.4. Emergy Sustainability Index (ESI)

ESI arises from the ratio of EYR to ELR. It measures the contribution of a resource or process to the economy per unit of environmental loading. To be sustainable, a process or system must obtain the highest yield ratio at the lowest environmental loading ratio [61]. The higher this index, the more an economy relies on renewable energy sources. A low ESI (less than one) indicates a highly developed consumer-oriented economy, whereas a high ESI (greater than 10) indicates an economy that is termed "undeveloped". The ESI ratios between one and 10 are referred to as "developing economies" [62].

The PPRD as a whole has ESI values of less than one, which indicates that this developed region is a "consumer"-oriented economy that relies highly on non-renewable energy resources, such as fossil fuels. Among the nine provinces, only Hainan has an ESI value (2.145) higher than one. Guangdong has the lowest ESI (0.071), while the ESI values of Fujian, Guangxi, Hunan and Jiangxi are lower than 0.5, indicating that the economies in these provinces overly rely on non-renewable and imported resources.

3.2. Emergy-Based Ternary Diagram Analysis

Figure 6 shows the ternary diagrams of nine provinces in PPRD. Points 1 to 9 successively represent Fujian, Guangdong, Guangxi, Guizhou, Hainan, Hunan, Jiangxi, Sichuan and Yunnan, respectively.

In Figure 6a, Points 2, 4 and 6–9 are represented by the resource flow lines R = 5%, N = 60% and F = 35%. Guangdong, Guizhou, Hunan and Jiangxi use nearly the same percentage (5%) of local renewable resources, but the sustainability of Guangdong (ESI < 0.1) is obviously lower than that of

Guizhou (ESI > 0.5), as shown in Figure 6b. Similarly, Hunan and Sichuan utilize an equal amount of local non-renewable resources (60%), but Sichuan is more sustainable.

Figure 6. Ternary diagrams of the nine provinces in the Pan-Pearl River Delta: (**a**) resource flow lines; (**b**) sustainability lines; (**c**) sensitivity lines; and (**d**) symergy point (the points of each system refer to the region empower). Points: (1) Fujian; (2) Guangdong; (3) Guangxi; (4) Guizhou; (5) Hainan; (6) Hunan; (7) Jiangxi; (8) Sichuan; and (9) Yunnan.

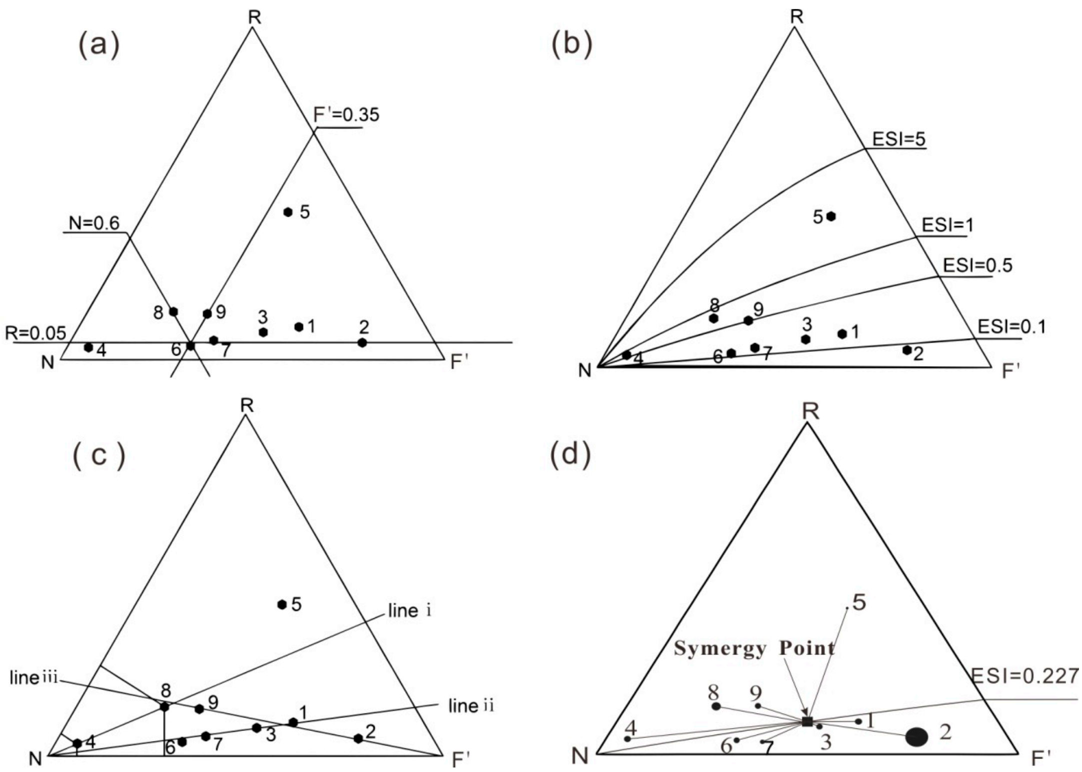


Figure 6b shows the sustainability lines for nine provinces. As pointed out by Brown and Ulgiati [63], ESI indices that are less than one are indicative of regions that are unsustainable in the long run, whereas those greater than five are indicative of regions with long-term sustainability. Among the nine provinces in PPRD, only Hainan is located above the line ESI = 1, whereas the others are located below the line ESI = 1. Fujian, Guangxi, Hunan and Jiangxi are even located below the line ESI = 0.5. Guangdong is located below the line ESI = 0.1 and is severely unsustainable.

Figure 6c shows the sensitivity lines of PPRD. The line *i* joining the apex N to Point 4 also passed Point 8, which means that, relative to Guizhou, Sichuan is operating with lower quantities of non-renewable resources, with R and F remaining present at the same proportion. Thus, improving the sustainability of Guizhou is possible just by decreasing the quantities of non-renewable resources and maintaining the proportion between the economic investment and the quantity of renewable resources. Similarly, Points 1, 3, 6 and 7 lie on or close to the line *ii*. Thus, the difference in quantity of local non-renewable resources accounts for the variance of sustainability among Fujian, Guangxi, Hunan and Jiangxi. The lines *i* and *ii* indicate a hierarchy for action. Instead of randomly changing all variables to enhance the sustainability of Guizhou, Guangxi, Hunan and Jiangxi, the priority is clearly decreasing the use of non-renewable resources. Decreasing the purchased services of Guangdong, Fujian and Yunnan may enhance their sustainability and make it equivalent to or higher than that of Sichuan, as shown in line *iii*.

As shown in Figure 6d, the symergy point, based upon the nine provinces, presents an ESI = 0.227, indicating that the PPRD region as a whole is characterized by long-term unsustainability. The point of each province refers to the corresponding region empower; thus, the low sustainability of Guangdong Province has the largest influence on the low sustainability of the whole PPRD region.

3.3. Emergy-Based Spatial Analysis

3.3.1. Emergy Maps

Figures 7 and 8 present the results of emergy maps for PPRD and its provinces. The pattern of emergy flows in these maps illustrates the resource consumption using two parameters: (1) the quantities consumed based on their environmental costs; and (2) the location of consumption.

Figure 7 shows the distribution of total emergy use in the nine provinces. Guangdong has the highest emergy consumption rate, mainly because of its active economy. Sichuan has the second highest emergy consumption rate, although its total emergy use is only half of Guangdong's. Nevertheless, provinces adjoining Guangdong have a relatively lower emergy consumption rate. Particularly, consumption intensity decreases to a minimum in Hainan and Jiangxi, where the economic contributions are lower and fewer resources are utilized.

Figure 7. Total emergy use map of PPRD region.

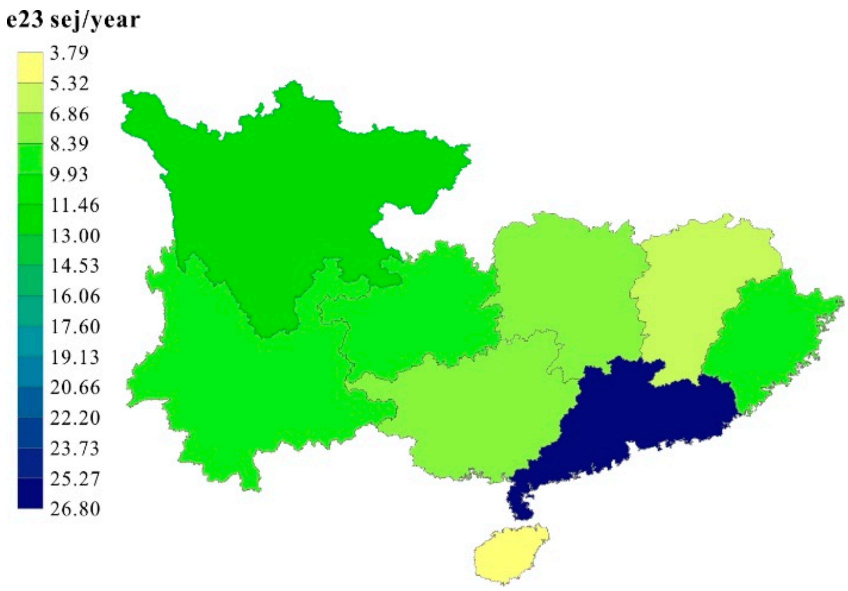
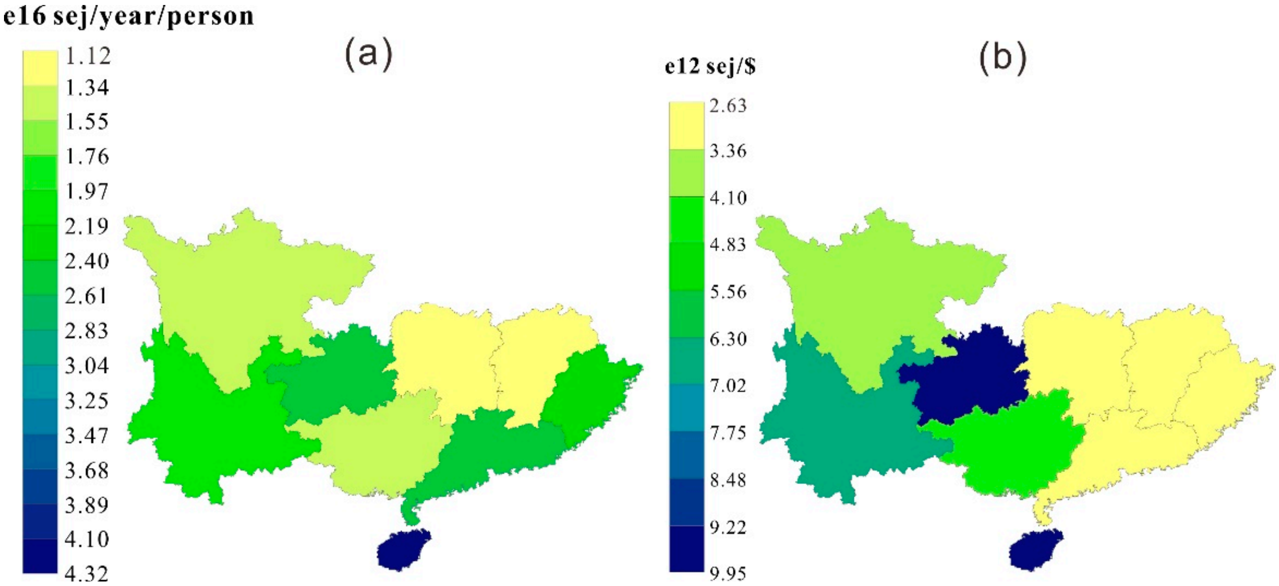


Figure 8a illustrates the distribution of emergy per person value across the PPRD region. Moving north from Hainan, the emergy per person values exhibit a decreasing trend. The emergy per person value can be utilized to measure the potential average standard of living of a population. Population size is one of the key factor determining the living standard in a region. Guangdong has the highest value of total emergy use, but not the emergy per person value, owing to its huge population size. By contrast, Hainan has the highest emergy per person value among the provinces in PPRD, although it has the least total emergy use.

Figure 8b shows the emergy-to-money ratio across the PPRD region. The emergy-to-money ratio is an appropriate measure for evaluating an economy. The higher an economy is developed, the lower its emergy-to-money ratio. Less developed regions have more rural areas and utilize more direct input from environment resources for their people [47]. As shown in Figure 8b, the four provinces in the east of PPRD have an emergy-to-money ratio lower than 3.36×10^{12} sej/$. Guizhou and Hainan have relatively high emergy-to-money ratios, both of which are higher than 9×10^{12} sej/$.

Figure 8. (**a**) Emergy per person map. (**b**) Emergy-to-money ratio map.



3.3.2. Emergy Density Map

Emergy density, as a function of total emergy consumption and total land area, can reflect the intensity of land development and human activities. The emergy density map of the PPRD region (see Figure 10a) exhibits a decreasing trend from Guangdong to its surrounding provinces. Yunnan and Sichuan have the lowest emergy density among nine provinces in the PPRD.

However, human activities, whether industrial production or agricultural cultivation, are mainly performed in the flat land. Thus, the emergy density map based on the total area of a region cannot fully reflect the intensity of land development and human activities. The pressure of economic investment on the local environment is underestimated.

In the PPRD region, the distribution of flat land in nine provinces is heterogeneous (see Figure 9). The proportions of flat land in Hunan, Jiangxi and Hainan are obviously higher than those in other provinces. The flat land of Sichuan only accounts for less than 20% of its total land area.

Thus, emergy density based on flat land area is proposed to reflect the pressure of economic investment on the local environment. The emergy density map based on the flat land of the PPRD region is exhibited in Figure 10b. On the one hand, most of the provinces have emergy density values higher than 1 × 1019 sej/year/km^2, a value that means an immoderate land exploration and utilization. On the other hand, some provinces, such as Sichuan, Yunnan, Guizhou and Fujian, show a more serious land exploration status, because of their limited flat land. By contrast, Jiangxi and Hunan have relatively lower emergy density and have spare space for further development.

Figure 9. Distribution of flat land in nine provinces of the PPRD region. Based on 30 × 30-m resolution digital elevation model (DEM) of PPRD, we calculated the difference (D-value) between the maximum (Max (H)) and minimum (Min (H)) values of elevation in a 3 × 3 kernel by employing focal range analysis in GIS tools. The flat land consists of grids whose D-value is less than or equal to 30 meters.

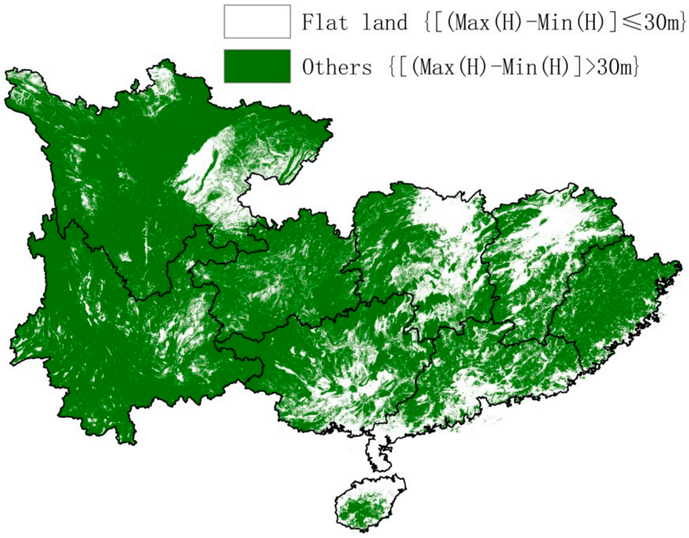
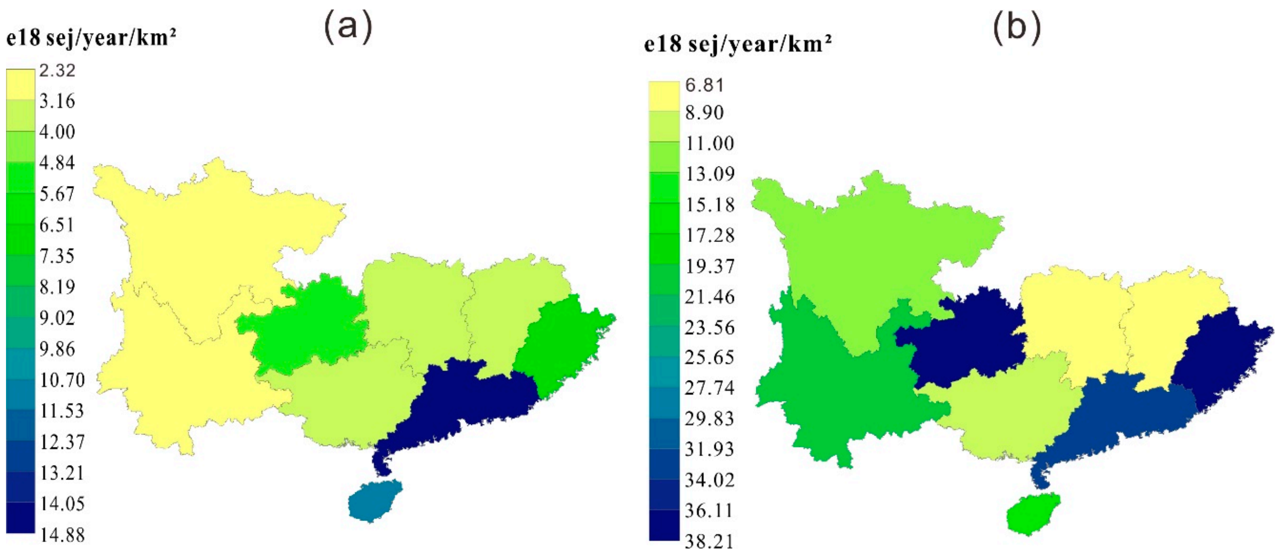


Figure 10. (**a**) Emergy density map based on the total area of the PPRD region. (**b**) Emergy density map based on the flat land area of the PPRD region.



4. Conclusions and Suggestions

In this paper, emergy synthesis was used in association with the GIS and ternary diagrams to assess the sustainability of PPRD and its provinces. The main resource flows are quantified and converted to emergy form by the corresponding transformity functions. Emergy accounting of PPRD is estimated, and various emergy-based indicators are reported. Ternary diagrams for the nine provinces of PPRD are drawn to provide a graphical representation of the emergy accounting data. Finally, the GIS tool is employed to assist in the emergy-based spatial analysis.

Analysis of the emergy indicator for PPRD and its nine provinces shows that Guizhou and Sichuan, especially Guizhou, have high EYR and are, thus, the main energy suppliers in PPRD. However, the ELR value (26.26) of Guizhou indicates that the current economic approach of the province is unsustainable, because it relies mainly on non-renewable resources. The ELR value (1.26) of Hainan indicates that the province creates a firm balance between emergy use of renewable and non-renewable resources, whereas those ELR values of Fujian and Guangdong indicate that these two provinces depend on purchase inputs more than local generations.

The emergy-based ternary diagram analysis shows the resource flow lines, sustainability lines, sensitivity lines and symergy points of PPRD. The resource flow and sustainability lines show that Guangdong, Guizhou, Hunan and Jiangxi use nearly the same percentage of local renewable resources, but the sustainability of Guangdong is obviously lower than Guizhou. Likewise, Hunan and Sichuan utilize an equal amount of local non-renewable resources, but Sichuan is more sustainable. The sensitivity lines show that improving the sustainability of Guizhou is possible just by decreasing the quantities of non-renewable resources and maintaining the proportion between the economic investment and the quantity of renewable resources. Decreasing the purchased services of Guangdong, Fujian and Yunnan may also enhance their sustainability and make it equivalent to or higher than that of Sichuan. The symergy point indicates that the PPRD region as a whole, with a value (0.227) of ESI significantly lower than one, is unsustainable in the long run.

The emergy-based spatial analysis generated emergy maps in the form of emergy geography. These maps are multidimensional illustrations that show resource consumption, emergy per person, the emergy-to-money ratio and emergy density across the PPRD. The emergy density based on flat land area is mapped to reflect the intensity of emergy use in the human activity area. Compared with emergy density based on total land area, the emergy density based on flat land area can reveal the actual stress that human activities exert on the ecosystem.

The above-mentioned conclusions reveal that the current development path of PPRD region is unsustainable in the long run. Therefore, provinces in PPRD should take some measures to improve their performances in the future. On the one hand, enhancing the ratio of renewable resources in the total energy consumption is necessary [64], and more attention should be paid to the exploitation of marine resources and the rapid development of the oceanic economy [65,66]. The ocean contains abundant resources, most of which are renewable. Guangdong, Guangxi, Fujian and Hainan have vast sea areas waiting to be cultivated and developed. The reasonable development of marine resources will inevitably enlarge the ratio of renewable resources in the total emergy use and, thus, improve the sustainability of these provinces and the PPRD region. On the other hand, many provinces, such as Guizhou, Hunan and Sichuan, should urgently decrease their non-renewable resource use by speeding up changes in their economic development and adjusting their economic structures. The service industry, such as tourism, is slightly dependent on non-renewable resources and should be the pillar in this area [67]. The provinces of PPRD, as the natural capital storage of China, have beautiful sceneries and unique geomorphic features, making them very suitable for the tourism industry.

For future studies, a time series analysis (*i.e.*, a retrospective analysis and forecast of the future development of human activities on the territory) can be implemented to achieve suitable environmental management aimed toward sustainability. As suggested by Pulselli [3], a constant monitoring of emergy flows and their elaboration through GIS will provide information about the current trends of environmental resource use.

Acknowledgments

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Author Contributions

All authors conceived of the study and wrote the paper. Guomin Li performed the data collection, data analysis, article writing and formatting.

Appendix

This section includes raw data and detailed calculations for emergy flows in Table A1.

Table A1. The raw data and detailed calculations of emergy flow in PPRD.

No.	Item	Raw data and Calculations		
		Renewable Resources (R):		
1		Solar Energy:		
	Continental Shelf Area =	1.28×10^{12}	m^2	
	Land Area =	2.01×10^{12}	m^2	
	Insolation =	120	$Kcal/cm^2/year$	
	Albedo =	0.2	(given as decimal)	
	Energy (J) =	(area incl shelf) × (avg insolation) × (1-albedo)		
	=	(_ m^2) × (_ $Cal/cm^2/year$) × (1.0×10^4 cm^2/m^2) × (1-albedo) × (4186 J/kcal)		
	=	1.32×10^{22}	J/year	
2		Rain, Chemical Potential Energy:		
	Land Area =	1.28×10^{12}	m^2	
	Continental Shelf Area =	2.01×10^{12}	m^2	
	Rain (land) =	1.51	m/year	
	Rain (shelf) =	0.68	m/year	(est. as 45% of tot. rain)
	Evapotrans rate=	1.21	m/year	(est. as 80% of tot. rain)
	Energy (land) (J)=	(area)(Evapotrans)(Gibbs No.)		
	=	(_ m^2) × (_ m) × (1000 kg/m^3) × (4.94×10^3 J/kg)		
	=	7.69×10^{18}	J/year	
	Energy (shelf) (J)=	(area of shelf)(Rainfall)(Gibbs No.)		
	=	6.76×10^{18}	J/year	
	Total energy (J) =	1.44×10^{19}	J/year	
3		Rain, Geopotential Energy:		
	Area =	1.28×10^{12}	m^2	
	Rainfall =	1.51	m	

Table A1. *Cont.*

No.	Item	Raw data and Calculations		
	Average Elevation =	1324.21	m	
	Runoff rate =	0.2	%	(percent, given as a decimal)
	Energy (J) =	(area)(rainfall)(% runoff)(Average Elevation)(gravity)		
	=	(_ m^2) × (_ m) × (_ %) × (1000 kg/m^3) × (_ m) × (9.8 m/s^2)		
	=	5.05×10^{18}	J/year	
4		Wind Energy:		
	Area =	1.28×10^{12}	m^2	
	Density of Air =	1.3	kg/m^3	
	Average annual wind velocity =	6.27	m/s	
	Geostrophic wind =	10.45	m/s	observed winds are about 0.6 of geostrophic wind
	Drag Coefficient =	1.00×10^{-3}		
	Energy (J) =	(area)(air density)(drag coefficient)($velocity^3$)		
	=	(_ m^2)(1.3 kg/m^3)(1.00×10^{-3})(_ m/s)(3.14×10^7 s/year)		
	Energy (J) =	5.99×10^{19}	J/year	
5		Wave Energy:		
	Shore length =	1.87×10^7	m	
	Wave height =	1	m	
	Energy (J) =	(shore length)(1/8)(density)(gravity)(wave $height^2$)(velocity)		
	=	(_ m)(1/8)(1.025×10^3 kg/m^3)(9.8 m/s^2)(_ $m)^2$(_ m/s)(3.14×10^7 s/year)		
	Energy (J) =	3.28×10^{18}	J/year	
6		Tidal Energy:		
	Continental Shelf Area =	1.28×10^{12}	m^2	
	Average Tide Range =	1.2	m	
	Density =	10^{25}	kg/m^3	
	Tides/year =	730		(estimation of 2 tides/day in 365 days)
	Energy (J) =	(shelf) (0.5)(tides/year)(mean tidal $range)^2$(density of seawater)(gravity)		
	=	(_ m^2) × (0.5) × (_ /year) × (_ $m)^2$ × (_ kg/m^3) × (9.8m/s^2)		
	=	6.78×10^{18}	J/year	
7		Earth Cycle		
	Land Area =	2.01×10^{12}	m^2	
	Heat flow =	1.45×10^6	J/m^2	
	Energy (J) =	(area)(Heat flow)		
	Energy (J) =	(_ m^2)(1.0×10^6 J/m^2)		
	=	2.91×10^{18}	J/year	
		Nonrenewable Resources from within Country(N)		
		Dispersed Rural Source (N_0)		
8		Hydroelectricity:		
	Kilowatt h/year =	4.31×10^{11}		KwH/year (assume 80% load)
	Energy (J) =	(Energy production)(energy content)		
	Energy (J) =	(_ KwH/year) × (3.6×10^6 J/KwH)		
	=	1.55×10^{18}	J/year	

Table A1. *Cont.*

No.	Item	Raw data and Calculations		
9		Agricultural Production:		
	Production =	6.26×10^8	MT	(dry mass, 20% humidity)
	Energy (J) =	(Total production)(energy content)		
	Energy (J) =	(_ MT) × (1.0×10^6 g/MT) × (80%) × (4.0 kcal/g) × (4186 J/kcal)		
	=	8.38×10^{18}	J/year	
10		Livestock Production:		
	Livestock Production =	3.12×10^7	MT	(80% humidity)
	Energy (J) =	(Total production)(energy content)		
	Energy (J) =	(_ MT) × (1.0×10^6 g/MT) × (20%) × (5.0 KCal/g) × (4186 J/KCal)		
	=	1.31×10^{17}	J/year	
11		Fisheries Production:		
	Fish Catch =	2.42×10^7	MT	(80% humidity)
	ENERGY (J) =	(Total production)(energy content)		
	Energy (J) =	(_ MT) × (1.0×10^6 g/MT) × (5.0 KCal/g) × (20%) × (4186 J/KCal)		
	=	1.01×10^{17}	J/year	
12		Fuelwood Production:		
	Fuelwood Prod =	3.55×10^6	m^3	
	Energy (J) =	(Total production)(energy content)		
	Energy (J) =	(_ m^3)(0.5×10^6 g/m^3)(3.6 kcal/g)(80%)(4186 J/kcal)		
	=	2.14×10^{16}	J/year	
13		Forest Extraction		
	wood Harvest =	4.44×10^7	m^3	
	bamboo Harvest =	4.09×10^7	MT	
	Energy (J) =	(Total production)(energy content)		
	wood Energy (J) =	(_ m^3)(0.5×10^6 g/m^3)(80%)(3.6 kcal/g)(4186 J/kcal)		
	=	2.68×10^{17}	J/year	
	bamboo Energy (J) =	(_ MT)(1.0×10^6 g/MT)(80%)(3.6 kcal/g)(4186 J/kcal)		
	=	4.93×10^{17}	J/year	
	Total =	7.61×10^{17}	J/year	
14/15		Topsoil and Som:		
	Harvested cropland =	4.82×10^{11}	m^2	
	Soil loss =	840	g/m^2/year	
	Average organic content (%) =	3	%	
	Energy (J) =	(_ g/m^2/year) × (_ m^2) × (% organic) × (5.4 Kcal/g)(4186 J/Kcal)		
	=	2.75×10^{17}	J/year	
	Mass (g) =	4.05×10^{14}	g/year	
		Concentrated Use (N1)		
16		Natural Gas		
	Consumption =	1.82×10^{10}	m^3/year	
	Energy (J) =	(_ m^3/year)(energy content)		
	Energy (J) =	(_ m^3/year) × (8,966 kcal/m^3) × (4186 J/kcal)		
	=	6.85×10^{17}	J/year	

Table A1. *Cont.*

No.	Item	Raw data and Calculations			
17		Oil			
	Consumption =	1.97×10^{11}	L/year		
	Energy (J) =	(_ L/year)(energy content)			
	Energy (J) =	(_ L/year) × (1.14×10^4 kcal/L) × (4186 J/kcal)			
	=	9.40×10^{18}	J/year		
18		Coal			
	Consumption =	4.87×10^8	MT/year		
	Energy (J) =	(_ MT/year)(energy content)			
	Energy (J) =	(_ MT/year) × (2.9×10^{10} J/Mt)			
	=	1.41×10^{19}	J/year		
19		Minerals (Including Limestone and Fertilizers)			
		Consumption		Transformity	
	Limestone =	9.06×10^8	MT/year	1.61×10^9	sej/g
	Phosphorus =	2.50×10^7	MT/year	1.40×10^{10}	sej/g
	Potash =	0.00	MT/year	2.80×10^9	sej/g
	Nitrogen =	1.25×10^7	MT/year	7.41×10^9	sej/g
	Total Consumption =	9.43×10^8	MT/year		
	Mass (g) =	(_ MT/year) × (1.0×10^6 g/MT)			
	=	9.43×10^{14}	g/year		
	Transformity(weighted) =	2.01×10^9	sej/g		
20	Metals (Mined-Al, Au, Cu, Fe, others)			Transformity	
	Aluminum =	5.95×10^6	MT/year	1.37×10^9	sej/g
	Iron =	2.19×10^8	MT/year	1.44×10^9	sej/g
	Copper =	2.69×10^5	MT/year	1.55×10^8	sej/g
	Gold =	3.35	MT/year	4.04×10^8	sej/g
	Others =	5.78×10^6	MT/year	1.61×10^9	sej/g
	Consumption =	2.31×10^8	MT/year		
	Mass (g) =	(_ MT) × (1.0×10^6 g/MT)			
	=	2.31×10^{14}	g/year		
	Transformity(weighted) =	7.57×10^7	sej/g		
		Imports and Outside Sources (F'):			
		Imported Fuels and Minerals (F)			
21	Fuels:				
	Natural gas =	1.82×10^{10}	m^3/year		
	Energy (J) =	(_ m^3/year) × (8966 kcal/m^3) × (4186 J/kcal)			
	Oil derived fuels =	1.97×10^{11}	L/year		
	Energy (J) =	(_ L/year) × (1.14×10^4 kcal/L) × (4186 J/kcal)			
	Coal =	4.87×10^8	MT/year		
	Energy (J) =	(_ MT/year) × (2.9×10^{10} J/Mt)		Transformity	
	Natural gas =	6.85×10^{17}	J/year	5.88×10^4	sej/j
	Oil derived fuels =	9.40×10^{18}	J/year	1.06×10^5	sej/j
	Coal =	1.41×10^{19}	J/year	6.41×10^4	sej/j
	=	2.42×10^{19}	J/year		
	Transformity(weighted) =	8.03×10^4	sej/j		

Table A1. *Cont.*

No.	Item	Raw data and Calculations			
22	Metals:			Transformity	
	Aluminum ore (Bauxite) =	3.13×10^{3}	MT/year	1.37×10^{9}	sej/g
	Aluminum =	4.90×10^{5}	MT/year	1.25×10^{10}	sej/g
	Iron ore =	2.74×10^{7}	MT/year	1.38×10^{9}	sej/g
	Steel =	5.88×10^{6}	MT/year	4.13×10^{9}	sej/g
	Copper wire =	1.96×10^{6}	MT/year	1.59×10^{11}	sej/g
	Gold =	3.92	MT/year	4.04×10^{8}	sej/g
	Others =	3.42×10^{6}	MT/year	1.61×10^{9}	sej/g
	Imports =	3.92×10^{7}	MT/year		
	Mass (g) =	(_ MT/year) × (1.0×10^{6} g/MT)			
	=	3.92×10^{13}	g/year		
	Transformity(weighted) =	9.85×10^{9}	sej/g		
23	Minerals:			Transformity	
	Cement =	6.41×10^{3}	MT/year	1.97×10^{9}	sej/g
	Phosphorus =	1.28×10^{4}	MT/year	2.87×10^{10}	sej/g
	Potash =	2.89×10^{6}	MT/year	2.80×10^{9}	sej/g
	Nitrogen =	2.95×10^{6}	MT/year	7.41×10^{9}	sej/g
	Others =	5.58×10^{5}	MT/year	1.61×10^{9}	sej/g
	Imports =	4.21×10^{5}	MT/year		
	Mass (g) =	(_ MT/year) × (1.0×10^{6} g/MT)			
	=	4.21×10^{11}	g/year		
	Transformity(weighted) =	7.41×10^{10}	sej/g		
	Imported Goods (G)				
24	Food and Agricultural Products				
	Imports =	3.33×10^{7}	MT/year		
	Energy (J) =	(_ MT/year) × (1.0×10^{6} g/MT) × (3.5 Kcal/g) × (4186 J/Kcal) × (80%)			
	=	3.90×10^{17}	J/year		
25	Livestock, Meat, Fish				
	Imports =	2.58×10^{5}	MT/year		
	Energy (J) =	(_ MT/year) × (1.0×10^{6} g/MT) × (5 Kcal/g) × (4186 J/Kcal) × (0.22 protein)			
	=	1.19×10^{15}	J/year		
26	Plastics and Rubber				
	Imports =	5.16×10^{6}	MT/year		
	Energy (J) =	(_ MT/year) × (1000 Kg/MT) × (30.0×10^{6}J/kg)			
	=	1.55×10^{17}			
27	Chemicals				
	Imports =	1.29×10^{7}	MT/year		
	Mass (g) =	(_ MT/ year)×(1.0×10^{6} g/MT)			
	=	1.29×10^{13}	g/year		
28	Finished Materials (lumber, paper, textiles, glass, others)			Transformity	
	Lumber =	9.46×10^{6}	MT/year	8.80×10^{8}	sej/g
	Paper =	5.68×10^{6}	MT/year	3.69×10^{9}	sej/g

Table A1. *Cont.*

No.	Item	Raw data and Calculations			
	Others =	3.78×10^6	MT/year	5.85×10^9	sej/g
	Imports =	1.89×10^7	MT/year		
	Energy (J) =	(_ MT/year) × (1.0 × 10^6 g/MT)			
	=	1.89×10^{13}	g/year		
	Transformity(weighted) =	2.72×10^9	sej/g		
29	Machinery, Transportation, Equipment				
	Imports =	3.94×10^9	$US		
	Emergy of Services in Imported Goods and Fuels (P_2I):				
30	Imported Services:				
	Dollar Value =	4.99×10^{11}	$US		
	EXPORTS:				
	Exported production (B)				
31	Food and Agricultural Products				
	Exports:	1.75×10^7	MT/year		
	Energy (J) =	(_ MT) × (1.0 × 10^6 g/MT) × (80%) × (3.5 Cal/g) × (4186 J/Cal)			
	=	2.05×10^{17}	J/year		
32	Livestock, Meat, Fish				
	Exports =	2.18×10^7	MT/year		
	Energy (J) =	(_ MT)(1.0 × 10^6 g/MT)(5 Cal/g)(4187 J/Cal)(0.22 protein)			
	=	1.00×10^{17}	J/year		
33	Finished Materials (lumber, paper, textiles, glass, others)			Transformity	
	Lumber =	1.84×10^6	MT/year	8.80×10^8	sej/g
	Paper =	2.94×10^6	MT/year	3.69×10^9	sej/g
	Others =	2.57×10^6	MT/year	5.85×10^9	sej/g
	Exports =	7.36×10^6	MT/year		
	Energy (J) =	(_ Mt)(1.0 × 10^6 g/MT)			
	Total =	7.36×10^{12}	g/year		
	Transformity(weighted) =	3.74×10^9	sej/g		
34	Machinery, Transportation, Equipment				
	Exports =	2.58×10^{11}	$US		
35	PLASTICS & RUBBER				
	Exports =	4.36×10^6	MT/year		
	Energy (J) =	(_ MT/year) × (1000 Kg/MT) × (30.0 × 10^6 J/kg)			
	=	1.31×10^{17}			
	Exported without Use(N_2)				
36	Fuels:				
	Natural gas =	1.15×10^{10}	m^3/year		
	Energy (J) =	(_ m^3/year) × (8966 kcal/m^3) × (4186 J/kcal)			
	Oil derived fuels =	4.21×10^{10}	L/y		
	Energy (J) =	(_ L/y) × (1.14 × 10^4 kcal/L) × (4186 J/kcal)			
	Coal =	8.96×10^7	MT/year		
	Energy (J) =	(_ MT/year) × (2.9 × 10^{10} J/Mt)		Transformity	
	Natural gas =	4.33×10^{17}	J/year	5.88×10^4	sej/j

Table A1. *Cont.*

No.	Item	Raw data and Calculations			
	Oil derived fuels =	2.01×10^{18}	J/year	1.06×10^{5}	sej/j
	Coal =	2.60×10^{18}	J/year	6.41×10^{4}	sej/j
	Total Fuels =	5.04×10^{18}	J/year		
	Transformity(weighted) =	8.04×10^{4}	sej/j		
37		Metals:		Transformity	
	Aluminum ore (Bauxite) =	0.00	MT/year	1.37×10^{9}	sej/g
	Aluminum =	7.69×10^{5}	MT/year	1.25×10^{10}	sej/g
	Iron ore =	0.00	MT/year	1.38×10^{9}	sej/g
	Steel =	3.59×10^{6}	MT/year	4.13×10^{9}	sej/g
	Copper wire =	5.13×10^{5}	MT/year	1.59×10^{11}	sej/g
	Gold =	2.05	MT/year	4.04×10^{8}	sej/g
	Others =	2.56×10^{5}	MT/year	1.61×10^{9}	sej/g
	Exports =	5.13×10^{6}	MT/year		
	Mass (g) =	(_ MT) × (1.0×10^{6} g/MT)			
	=	5.13×10^{12}	g/year		
	Transformity(weighted) =	2.08×10^{10}	sej/g		
38		Minerals:		Transformity	
	Cement =	4.66×10^{5}	MT/year	1.97×10^{9}	sej/g
	Phosphorus =	9.32×10^{5}	MT/year	2.87×10^{10}	sej/g
	Potash =	1.55×10^{5}	MT/year	2.80×10^{9}	sej/g
	Nitrogen =	2.07×10^{6}	MT/year	7.41×10^{9}	sej/g
	Others =	1.55×10^{6}	MT/year	1.61×10^{9}	sej/g
	Exports =	5.18×10^{6}	MT/year		
	Mass (g) =	(_ Mt)(1.0×10^{6} g/Mt)			
	=	5.18×10^{12}	g/year		
	Transformity(weighted) =	8.87×10^{9}	sej/g		
39		Chemicals:			
	Exports =	6.87×10^{5}	MT/year		
	Mass (g) =	(_ MT)×(1.0×10^{6} g/MT)			
	=	6.87×10^{11}	g/year		
		Emergy Value of Service Exports (P_1E):			
40		Services IN Exports:			
	Dollar Value =	6.25×10^{11}	$US		

Conflicts of Interest

The authors declare no conflict of interest.

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