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Article

Emergy-Based Regional Socio-Economic Metabolism Analysis: An Application of Data Envelopment Analysis and Decomposition Analysis

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Abstract: Integrated analysis on socio-economic metabolism could provide a basis for understanding and optimizing regional sustainability. The paper conducted socio-economic metabolism analysis by means of the emergy accounting method coupled with data envelopment analysis and decomposition analysis techniques to assess the sustainability of Qingyang city and its eight sub-region system, as well as to identify the major driving factors of performance change during 2000–2007, to serve as the basis for future policy scenarios. The results indicate that Qingyang greatly depended on non-renewable emergy flows and feedback (purchased) emergy flows, except the two sub-regions, named Huanxian and Huachi, which highly depended on renewable emergy flow. Zhenyuan, Huanxian and Qingcheng were identified as being relatively emergy efficient, and the other five sub-regions have potential to reduce natural resource inputs and waste output to achieve the goal of efficiency. The results of decomposition analysis show that the economic growth, as well as the increased emergy yield ratio and population not accompanied by a sufficient increase of resource utilization efficiency are the main drivers of the unsustainable economic model in Qingyang and call for polices to promote the efficiency of resource utilization and to optimize natural resource use.

Keywords: socio-economic metabolism; emergy analysis; data envelopment analysis; decomposition analysis; Qingyang

1. Introduction

The process of economic development driven by industrialization can be seen as a transition from an agrarian to an industrial socio-metabolic regime [1]. The transition makes human society experience spectacular wealth accumulation, but it also causes large-scale ecological and social transformations [2]. Thus, the social-environmental relationship can be characterized as socio-economic metabolism [3,4]. The concept of socio-economic metabolism is applied to investigate the scale and composition of the socio-economic metabolic system [1,5–7] and to discuss its relationship with both economic growth [8], urbanization [5,9], industrialization [10,11] and environmental impacts [12]. The socio-economic metabolism perspective provides a useful framework for studying the interaction between human and natural systems [13] through quantifying the regional input-output amount and the structures of material and energy flows, the value of local resources and sustainability performance.

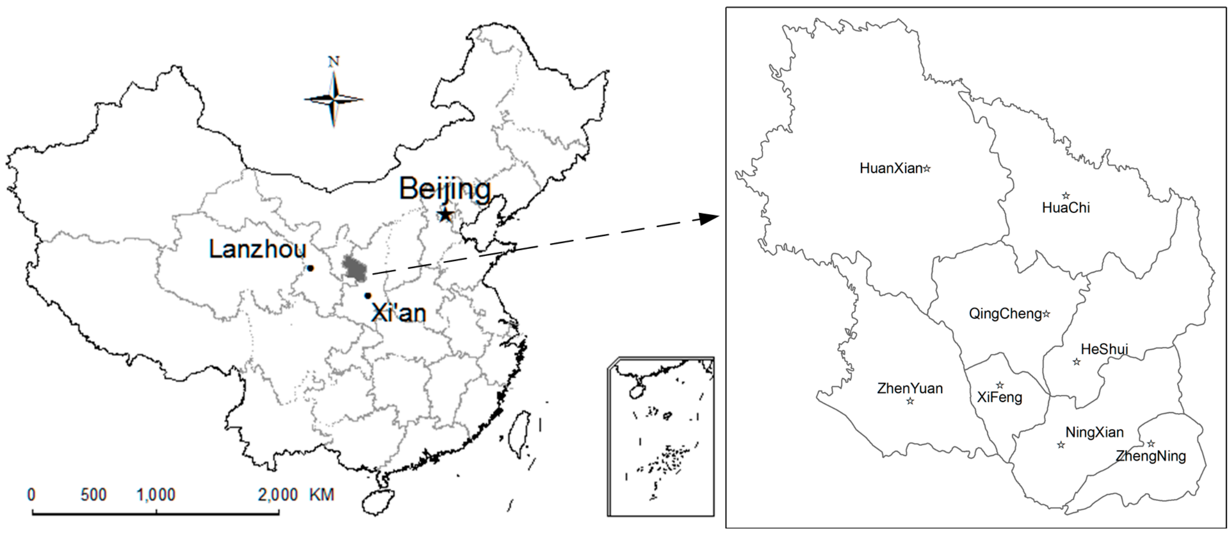
Nowadays, the term socio-economic metabolism has been widely applied in different fields, and related studies have been conducted at different levels, such as the household [14,15], industrial [10,16], urban [17–20] and regional level [21]. As for the regional level, related studies refer to quantifying material and the energy metabolic amount and the efficiency of different countries and regions, thus comparing the sustainability performance for different regional systems [22] by applying material flow analysis (MFA) [23], emergy analysis [20] and other integrated approaches (e.g., the multi-scale integrated analysis of socio-economic metabolism approach, MuSIASEM [21]).

As an instrument for aggregating various material flows into a few strategy indicators, MFA is applied to measure the weights of material inflows and outflows of socio-economic metabolism and can be broken into substance flow analyses (SFA), which deal with chemically-defined substances (such as phosphorus, copper, sulfur, *etc.*) in practical research [3]. However, the MFA-based socio-economic metabolism research has placed emphasis on the weight (quantities) of resource flows and ignored the varied qualities of material flows. Besides, the MFA-based metabolism studies provide strong and consistent evidence of the increasing consumption of resources in most economies, even in those economies that have focused their policies on dematerializing economic growth [24]. Emergy analysis, developed by Odum [25], is a technique of quantitative analysis that determines the values of resources, services and commodities in a common unit of solar energy, which allows all resources to be compared on a fair basis [26]. Therefore, emergy-based metabolism analysis, rather than the mass content of differing resources in the MFA, can overcome the limits of MFA that we mentioned above [3]. Moreover, emergy analysis provides an ecocentric bridge that connects economic and ecological systems and is a more holistic alternative to many existing methods for environmentally conscious decision making [27]. However, the emergy analysis has the problems of quantification, uncertainty and sensitivity, which also exist in all methods (such as MAF, LCA, exergy, *etc.*) that focus on a holistic view of industrial activity. In order to reduce the bias induced by the problems mentioned above, the paper integrated the emergy into data envelopment analysis, which is a nonparametric production frontier analysis approach and has been widely applied in micro- and macro-economic studies [24], to revise the results of emergy analysis and to provide decision makers with useful information regarding how to improve ecological efficiency. The paper also investigated the underlying determinant effects that influence the change of total emergy use by combining the methods of emergy and decomposition analysis. The present paper, taking Qiyang city and its eight sub-regions (Gansu Province, northwestern China) as the study case, investigates the features and findings of socio-economic metabolism.

2. Research Area

Qingyang city is located in the east part of Gansu province in northwestern China and ranges in latitude from 35°15′N to 37°10′N and in longitude from 106°20′E to 108°45′E, with a total administrative area of 27,119 km^2, consisting of one district, including Xifeng (XF), and seven counties, including Qingcheng (QC), Ningxian (NX), Zhengning (ZN), Huanxian (HX), Heshui (HS), Huachi (HC) and Zhenyuan (ZY) (Figure 1). Qingyang is one of the cradles of traditional Chinese farming culture and also is rich in crude oil and raw coal, with 3.25 billion tons of crude oil, 12 billion tons of raw coal and 1358.8 billion cubic-meters of coal-bed methane.

Figure 1. Qingyang city in China and the eight sub-regions.



In 2007, the GDP of Qingyang was $264 million, and GDP per capita was $1005, which was much lower than the average level of GDP per capita in China ($2,640). Qingyang is in the fast transition period from traditional agriculture to rapid industrialization [28], particularly after the discovery of abundant energy resources and the implementation of China's Western Development Program in 2000. With the large amount of exploitation and processing of energy resources, environmental pressure has increased rapidly. Thus, in the transition period, searching for a sustainable development model is a major task faced by local officials.

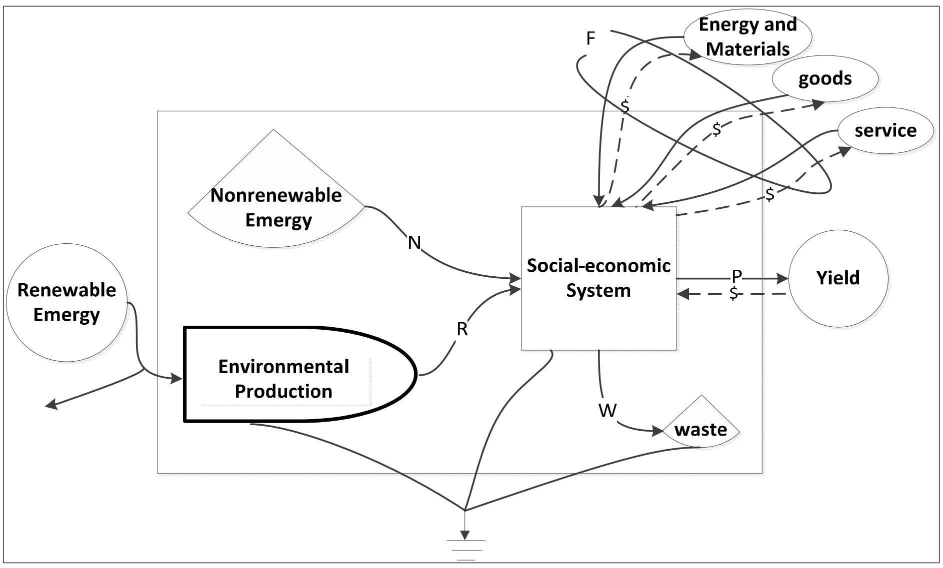
Specifically, the eight sub-regions in Qingyang all have their own distinctive features in the aspects of geography, environment and economy. For instance, XF is the political center of Qingyang region and is largely dependent on the inputs of energy, materials and products from outside. QC, with a relatively longer history of oil exploitation, is the main oilfield. NX and ZN, in the southeastern part of Qingyang, have certain similar features, such as rich coal resources and relatively developed agriculture. HX, in northern Qingyang, has a very high rate (99.8%) of soil erosion and water loss, as well as an underdeveloped economy. HS and HC have a relatively sound ecological environment and mid-level economic development. Economic development in ZY largely depends on the processing of agriculture products, especially apricot. Thus, to achieve sustainable development of Qingyang as a whole, differentiated policies regarding sustainable development, targeting each sub-region are crucial, as the each sub-region has special characteristics.

3. Research Methods

3.1. Emergy and Emergy Based Indicators

Emergy analysis is an environmental accounting method, which considers the energy system for the thermodynamics of an open system, aims to evaluate the contributory value of different material flows to the ecological economic system [29,30]. Emergy is measured in solar embodied joules, abbreviated sej. Emergy analysis characterizes all materials, energy, capital and services in equivalents of solar energy, *i.e.*, how much emergy would be required to do a particular task if the solar radiation were the only input [27,31–33]. Thus, the key part of emergy analysis is to transform the various materials and capital in human activities to a unified unit, sej [25], in which the key parameter is the emergy transformity (Trf.). The transformity of solar radiation is assumed equal to one by definition (1.0 sej/J), while the transformities of all of the other materials, energy and services are calculated based on their convergence patterns through the biosphere hierarchy [34]. Regarding emergy flows, renewable, nonrenewable and feedback emergy are three streams at the input side of the system. Additionally, output product emergy and waste emergy are two steams at the output side (Figure 2). The major steps of emergy analysis include identifying the system boundary, collecting eco-economic data, establishing emergy flow accounting, calculating a set of indices and ratios and using them to conduct the socio-economic metabolism analysis. Theoretically, all of the material, information and capital flows through the target studied region should be diagramed and then calculated. However, that is usually difficult, due to the lack of databases, especially for a city located in an undeveloped area in China. Therefore, the paper carried out a black box study without probing into the socio-economic metabolic structure thoroughly.

Figure 2. Emergy flows of a regional system.



Based on standard transformation, the emergy flow accounting was based on Qingyang and 8 sub-regions' raw data, which were from the QY Statistic Year Book (2001–2008), the XF, HX, HC, HS, ZN, ZY, NX, QC Statistic Year Books (2001–2008) [35–42] and investigations conducted on two planning programs: Qingyang Eco-City Development Program (investigation time period: August 11–19, 2008) and Qingyang Circular Economy Development Program (investigation time period: April 20–29, 2009); the corresponding indicators are given in Table 1. Additionally, the emergy transformity (Trf.) we used in this work relies on the transformities calculated by Odum and co-workers [33,43] (The averaged transformities of natural resources, products and processes used in this paper may lead to estimation bias to some extent, which was also shared by other approaches and is inevitable).

Table 1. The geographic and economic features of eight sub-regions and the whole (data of 2007).

		QY	XF	QC	ZN	NX	ZY	HX	HS	HC
Area (km^2)		27,119	996	2693	1321	2654	3501	9236	2942	3776
Average altitude (m)		1,310	1421	1310	1460	1310	1500	1612	1436	1440
Average rainfall (m/a)		0.53	0.5271	0.498	0.63	0.56	0.39	0.646	0.56	0.46
Population (1000 person)		2626.9	341	331.8	240.9	535.8	523.3	349.1	168.1	131.7
Population growth rate (‰)		7.41	7.12	7.26	7.50	7.12	7.10	7.76	7.54	7.45
GDP (million $)		2640.98	675.96	697.00	114.86	208.18	188.98	151.37	99.49	442.58
GDP per capita ($)		1005	1605	2112	478	385	363	432	585	3404
Industrial Structures	Primary (%)	16.15	11.5	7.17	40.30	36.58	42.17	20.30	40.84	5.80
	Secondary (%)	59.22	51.9	81.66	12.90	24.50	20.67	46.60	24.32	84.80
	Tertiary (%)	24.63	36.6	11.17	46.80	38.91	37.16	33.10	34.84	9.30

Notes: The abbreviations QY, XF, QC, ZN, NX, ZY, HX, HS and HC in the table represent Qingyang city, Xifeng district, Qingcheng, Zhengning, Ningxian, Zhenyuan, Huanxian, Heshui and Huachi, respectively.

3.2. Data Envelopment Analysis

Data envelopment analysis (DEA), which is a non-parametric frontier approach to evaluate the relative efficiency of a set of homogeneous decision-making units (DMUs) featuring multiple inputs and outputs, has recently been widely applied to analyze energy, environmental and ecological efficiency [44,45]. In recent empirical studies in the macroeconomic literature, GDP is commonly used as the output, and capital, labor and natural resources (water, energy, land and other mineral resources) are used as the input. The DEA efficiency model considering pollutants can be divided into three types. The first model takes pollutants as investment costs and, thus, is used to as the input. The second model is the data transfer function method, which considers the pollutants as ordinary output after transferring the-smaller-the-better undesirable output into the-bigger-the-better desirable output. The third model is the distance function method first proposed by Färe *et al.* (1994) [46] and then further extended by Chung (1997) [47], Tone (2001) [48] and other scholars. Because it can redeem the defect of the first two methods, such as no reflection on the real production process, strong convexity constraints, *etc.* [45], the distance function method has been widely applied to analyze ecological (or environmental) efficiency and environmental performance.

To comprehensively capture the physical flow (including inputs and outputs) of social and economic activities and to measure the ecological efficiency precisely, the inputs should include all kinds of inputs coming from the natural system and waste discharged into the environment. Usually, these inputs and outputs are measured in different measurement units. The emergy-based accounting system can solve the unit problem. In this paper, we combined the emergy-based accounting system and the undesirable output DEA model (slack-based undesirable output model) proposed by Tone (2001) to evaluate the ecological efficiency (EE) of the socio-economic metabolic system in Qingyang. A more detailed explanation of the model and its underlying mathematical procedures can be found in [48,49].

The paper uses the emergy content of natural resource inputs, production and waste emissions instead of mass content to construct aggregate input and output factors. The input factors include the nonrenewable input emergy (N) and feedback emergy (F), and the output factors include both the output product emergy (P), which is taken as a desirable output indicator, and waste emergy (W), which is taken as an undesirable output indicator. The score of ecological efficiency obtained by the slack-based undesirable output model is bounded by zero and one. If the score is upper-bounded to one, this means that it represents the best performance. Moreover, the lower the score, the worse the level of ecological efficiency [24,50].

3.3. Decomposition Analysis

Decomposition analysis is widely applied to investigate the underlying determinant factors that influence the change of energy consumption, CO_2 emissions, material usage, *etc.* [51–54]. Decomposition analysis covers two kinds of specific methods. The first one is structural decomposition analysis (SDA), which handles the input-output model. The second one is index decomposition analysis (IDA), which uses sector- or regional- level data. Because of requiring less data, the IDA has been applied to environmental and resource issues more extensively than SDA [55]. The decomposition analysis carried out in this paper is IDA based on the advanced sustainability analysis (ASA) approach, which was developed by the Finland Futures Research Center [56–58].

Since the decomposition analysis is capable of assessing the efficiency in the use of a given input in affecting a final result, it can be considered a fundamental tool to ease the monitoring and evaluation of the sustainability of economies and productive sectors/processes [59]. The knowledge of the major factors that affect a process' performance is essential for the design of new policy instruments and the evaluation of the implemented measures over a desired pattern of sustainability [60,61]. Moreover, decomposition analysis is necessarily dealing with complex indicators to avoid the loss of information [62,63].

ASA is designed to investigate the relationship between changes in environmental, economic and social variables that are measured by any preferred indicator or index. An equation describing the relationship between the factors (e.g., intensive factor V/X_1 and extensive factor X_1) contributing to variable V can be expressed in its simplest form as follows:

$$V = \frac{V}{X_1} \times X_1 \tag{1}$$

The procedure can be applied to multiple actors, as well. The two-factor decomposition presented above can be continued by taking a result from the first decomposition as a starting point for further decompositions, and the new results can then be decomposed again. The equation that identifies the contributing variables can be formulated in a general form as follows:

$$V = \frac{V}{X_2} \times \frac{X_2}{X_3} \times \ldots \times \frac{X_{n-1}}{X_n} \times X_n \quad (2)$$

A more detailed explanation of the ASA approach and its underlying mathematical procedures can be found in [64] and the DECOIN (2008) [65] and SMILE (2011) [66] websites.

4. Results

4.1. Overview of the Emergy Results of Qingyang and the Eight Sub-Regions

To characterize the metabolic structure and efficiency of the socio-economic system in Qingyang and its eight sub-regions, we calculated the emergy indices (Table 2). We found that the socio-economic system in Qingyang depended heavily on nonrenewable emergy, which occupied 61.13% of the total emergy input in 2007. Renewable emergy was the second largest input (23.54), followed by the feedback emergy input (15.32). The high value of the environment loading ratio (ELR = 3.25) and the low value of the emergy investment ratio (EIR = 0.18) refer to economic growth being greatly devoted to local non-renewable resources, which leads to high environmental pressure. An ESI (2.51) between one and ten means that Qingyang developed a "producer"-oriented economy that highly relied on non-renewable resources (Table 3).

XF, as the regional political center, mostly relied on feedback emergy, where the social-economic activity is supported by import emergy (96.76%). ZY also mainly relied on imported emergy (feedback emergy/total emergy input (F/U) is 54.99%). QC and ZN greatly depended on local non-renewable resources (U/nonrenewable input emergy (N) in the two sub-regions is greater than 50%). However, for HX and HC, the economic development highly relied on local renewable resources. The economic activities in NX and HS mainly depended on local renewable and non-renewable resources, respectively, but the dependence degree is less than HX and QC (Table 3).

The net emergy yield ratio (NEYR) is the ratio of the output emergy of the economic system to the feedback emergy from outside the region, which reflects the capability of local resources to support economic activities. Meanwhile, it shows the competitiveness of the economic system in supplying primary energy and resources [33]. The higher NEYR is, the higher the contribution of the regional economic system to the other regions is. In general, a value of NEYR of QY higher than five indicates that QY is an energy output region [67]. The NEYR of QC is the highest among the eight sub-regions, indicating the importance of QC in providing energy to the Qingyang economy. Additionally, this high value is due to the exploitation of non-renewable resources in QC. Conversely, the NEYR of XF is the lowest, which is caused by having the highest feedback emergy, as well as a higher EIR, emergy money ratio (EMR), emergy per capita (EPC) and emergy density (ED) compared to the average of QY, reflecting that XF has the strongest economic intensity and highest residential living conditions and ranks as the highest level of the economic system in QY city (Table 3).

Table 2. Indicators for emergy analysis in Qingyang.

Category	Emergy Index	Meaning	Calculation
Emergy Flows	Renewable Input Emergy (R)	local renewable resource input	
	Nonrenewable Input Emergy (N)	local nonrenewable resource input	
	Feedback Emergy (F)	feedback emergy from outside regions	
	Total Emergy Input (U)	total emergy input	R + N + F
	Output Product Emergy (P)	output emergy of products	
	Waste Emergy (W)	waste emergy discharged to the environment	
Emergy Structure	The Ratio of R, N and F to U	The ratio reflects the contributions of renewable, nonrenewable and feedback emergy to the total emergy input of the regional system at the input side	R/U; N/U; F/U
Emergy-Efficiency	Net Emergy Yield Ratio (NEYR)	NEYR reflects the supporting capability of local resources to economic development; meanwhile, it accounts for whether the economic system has competitiveness in supplying primary energy and resource [33,68]	P/F
	Emergy Investment Ratio (EIR)	EIR shows the efficiency of the usage of feedback emergy compared with local renewable and nonrenewable emergy.	F/(N + R)
	Emergy Money Ratio (EMR)	EMR shows the level of economic development. In general, a developed economic system has lower EMR as fast money circulation, while a rural area has higher EMR as a large percentage of unpaid local emergy input [33].	U/GDP
	Emergy Per Capita (EPC)	EPC reflects the residents' living standard from the emergy perspective.	U/population
	Emergy Density (ED)	ED shows spatial concentration of emergy flow within the regional system. Usually, a developed economic system has higher ED [33,68].	U/Area
Environment Pressure	Emergy Waste Ratio (EWR)	the waste discharge level in the input-side perspective	W/U
	Waste Output Ratio (WOR)	the waste discharge level in the output-side perspective	W/P
	Environment Loading Ratio (ELR)	ELR shows the pressure of social-economic activities on the local ecosystem [67].	(F + N)/R
Integrated Indicator	Emergy Sustainability Index (ESI)	A sustainable system should have higher NEYR and lower ELR. Usually, when ESI $<$ 1, it is a consumption system; when 1 $<$ ESI $<$ 10, it is an energetic system with enormous potentials for further development; while when ESI $>$ 10, the system is economically lagging behind [69–71]	NEYR/ELR

Table 3. The emergy analysis results of socio-economic metabolism in Qiyang (2007). sej, solar embodied joules.

	QY	XF	QC	ZN	NX	ZY	HX	HS	HC
Emergy Flows									
R (× 10^{20} sej)	**41.8**	1.81	5.15	2.44	4.29	3.37	15.3	1.55	4.19
N (× 10^{20} sej)	**108.6**	0.34	25.1	4.85	3.76	0.25	1.27	2.71	0.44
F (× 10^{20} sej)	**27.2**	64.4	1.69	0.51	2.54	4.39	4.95	2.26	1.09
P (× 10^{21} sej)	**2.22**	1.41	6.07	0.72	3.22	1.76	5.63	0.79	0.63
W (× 10^{19} sej)	**39.23**	9.31	7.78	7.31	3.71	0.7	1.13	5.69	3.61
Emergy Structure									
R/ U (%)	**23.54**	2.73	16.12	31.33	40.49	42.19	71.08	23.79	73.24
N/U (%)	**61.13**	0.51	78.58	62.18	35.49	2.82	5.91	41.58	7.7
F/ U (%)	**15.32**	96.76	5.3	6.49	24.01	54.99	24.01	34.63	19.03
Emergy Efficiency									
NYER	**8.15**	0.22	35.9	14.24	12.66	4.01	11.37	3.52	5.75
EIR	**0.18**	29.87	0.06	0.07	0.31	1.22	0.3	0.53	0.24
EMR (× 10^{12} sej/$)	**6.732**	9.85	4.58	6.79	5.09	4.23	1.42	6.55	1.29
EPC (× 10^{15})	**6.76**	19.5	9.62	3.24	2.16	1.53	6.16	5.66	17.7
ED (× 10^{11})	**6.5**	66.8	11.9	5.91	4.37	2.28	2.33	3.23	6.18
Environmental Pressure									
EWR	**0.022**	0.014	0.02	0.09	0.035	0.009	0.005	0.087	0.063
WOR	**0.018**	0.07	0.01	0.1	0.01	0.003	0.002	0.07	0.06
ELR	**3.25**	35.68	5.2	2.19	1.47	1.37	0.41	3.2	0.37
ESI	**2.51**	0.006	6.9	6.5	8.61	2.92	27.94	1.1	15.74

Notes: The abbreviations QY, XF, QC, ZN, NX, ZY, HX, HS and HC in the table represent Qingyang city, Xifeng district, Qingcheng, Zhengning, Ningxian, Zhenyuan, Huanxian, Heshui and Huachi, respectively.

The environment loading ratio (ELR) is the ratio of the sum of feedback and nonrenewable emergy to renewable emergy, which reflects the pressure of the social-economic process on the local ecosystem. The ELR of XF is highest (ELR = 35.68), reflecting high environmental pressure as a result of social economic activity. The ELR of QC (5.2) is the second highest and above the Qingyang average, due to its larger consumption of non-renewable resources (such as crude oil exploitation). On the other hand, the ELRs of the other five sub-regions are below Qingyang average. These regions can be considered as the areas with lower environmental pressure in terms of resources extraction and use (Table 3).

The emergy investment ratio (EIR) is the ratio of feedback (purchased) inputs to local resources (F/N + renewable input emergy (R)). The EIRs of XF and ZY are greater than one, indicating that the two regions relied more on purchased inputs than locally-available resources. However, the EIRs of the other six regions are less than one, indicating the need for local resources in these regions (Table 3).

The emergy sustainability index (ESI) is the ratio of NEYR to ELR. When ESI $<$ 1, it is a consumption system; when 1 $<$ ESI $<$ 10, it is an energetic system with the potential of further development; and when ESI $>$ 10, the system is economically lagging behind [72]. In general, the ESI of QY is between one and 10, which reflects that QY is an energetic regional system and has the potential for future development. Regarding the eight sub-regions, the ESI of XF is less than one, which reveals that XF is a consumption system. The ESIs of HX and HC are higher than 10, which shows that both regions are economically behind and economic development needs to be accelerated and strengthened. The ESIs of NX, QC, ZY, HS and ZN are between one and 10, where the economic development is energetic and robust (Table 3).

4.2. Emergy-Based Data Envelopment Analysis

Based on the emergy accounting database, the paper applied the undesirable-output DEA model to estimate the production frontier and calculate the ecological efficiency (EE) score of eight sub-regions in Qingyang using the input-oriented GRS (generalized returns-to-scale) framework. It is arguable to assume that there exists a production frontier for the eight sub-regions, because of the significant differences in the characteristics of the economic structures of those sub-regions.

The average EE score of eight sub-regions increased from 0.669 in the year 2000 to 0.766 in 2002, then decreased to 0.701 in 2006 and, finally, achieved an EE score of 0.728 in 2007. The EE scores of ZY and HX equal one during 2000–2007, which means that the two regions were identified as being relatively efficient. QC could be identified as an efficient region after 2002. The EE scores of NX, HS and HC decreased from 1.000, 0.309 and 0.805 to 0.802, 0.252 and 0.766. As for ZN, the EE score increased from 0.697 to 0.805. The emergy efficiency of XF was lowest among the eight sub-regions during the whole period (the EE score was below 0.2 in most years). In 2007, only three regions (QC, ZN and HX) were identified as efficient regions (Table 4).

Table 4. Summary of emergy efficiency evaluation.

	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
XF	0.115	0.117	0.133	0.087	0.116	0.162	0.213	0.198
QC	0.423	0.951	1.000	1.000	1.000	1.000	1.000	1.000
ZN	0.697	1.000	0.827	0.810	0.802	0.808	0.807	0.805
NX	1.000	0.584	1.000	1.000	1.000	0.816	0.528	0.802
ZY	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
HX	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
HS	0.309	0.268	0.294	0.344	0.284	0.268	0.292	0.252
HC	0.805	0.764	0.873	0.762	0.738	0.759	0.770	0.766
Average	0.669	0.711	0.766	0.750	0.743	0.727	0.701	0.728

Notes: The abbreviations QY, XF, QC, ZN, NX, ZY, HX, HS and HC in the table represent Qingyang city, Xifeng district, Qingcheng, Zhengning, Ningxian, Zhenyuan, Huanxian, Heshui and Huachi respectively.

4.3. Decomposition Analysis of Total Emergy Use

In order to understand the main drivers of the changes of total emergy flow (U), a decomposition equation was developed according to Equations (1) and (2). The time change of total emergy use (U) during 2000–2007 was decomposed as follows:

$$U = \frac{U}{F} \times \frac{F}{R+N} \times \frac{R+N}{GDP} \times \frac{GDP}{POP} \times POP \tag{3}$$

where F indicates feedback emergy flow, R is the value of all locally-available renewable emergy flows, N refers to the locally-available nonrenewable emergy flow, GDP is the value of gross domestic production and POP is the amount of population. According to Equation (3), changes of U are affected by five factors: U/F is the emergy yield ratio (EYR), which reflects the ability of a certain system to exploit available new emergy resources by investing local resources (local *versus* imported) [73]; F/(R + N) is the emergy investment ratio (EIR); (R + N)/GDP is the natural resource use per capital, which refers to the resource utilization rate; GDP/POP refers to the economic growth level; and POP refers to the population scale. The decomposition results of Qingyang and eight sub-regions are shown in Figures 3–11 with reference to the year 2000.

For Qingyang as a whole, the decomposition analysis (Figure 3) indicates that the factors, U/F, GDP/POP and POP, have increased the total emergy use and economic growth; GDP/POP was the main diver of the increasing emergy use. The factors (R + N)/GDP and F/(R + N) have decreased the emergy use. The negative contribution of the resource utilization rate, (R + N)/GDP, suggests policies to promote the efficiency of resource utilization.

Figure 3. Advanced sustainability analysis (ASA) decomposition of the total emergy use (U) in Qingyang during 2000–2007; the contributions of five factors to the percentage of the 2000 total emergy use (U) level. POP, population.

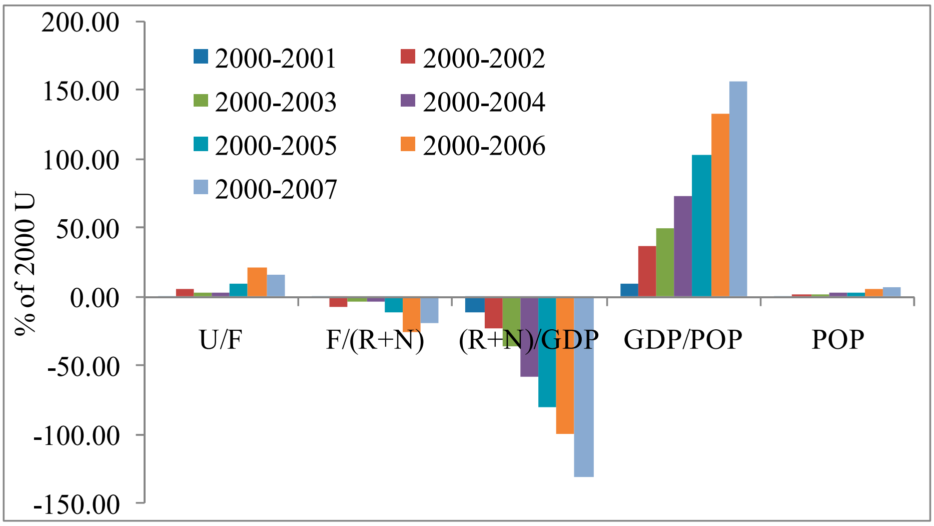
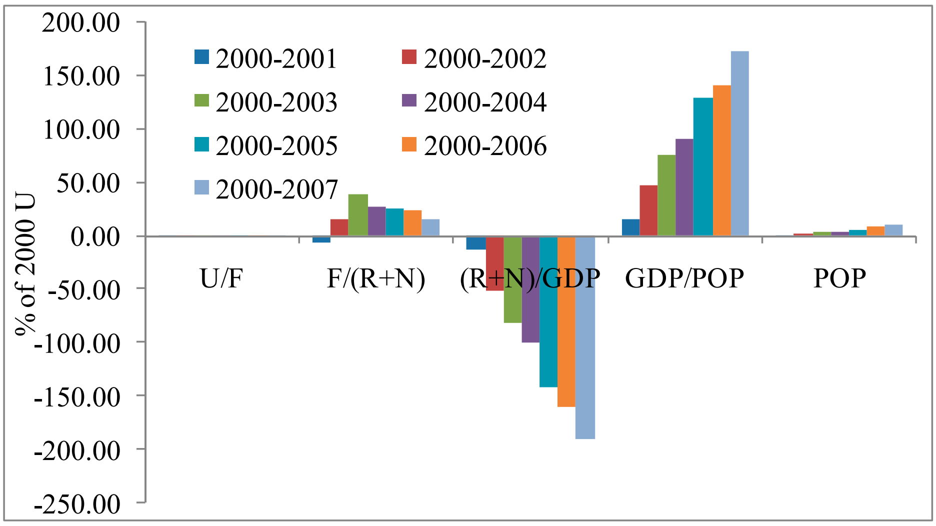


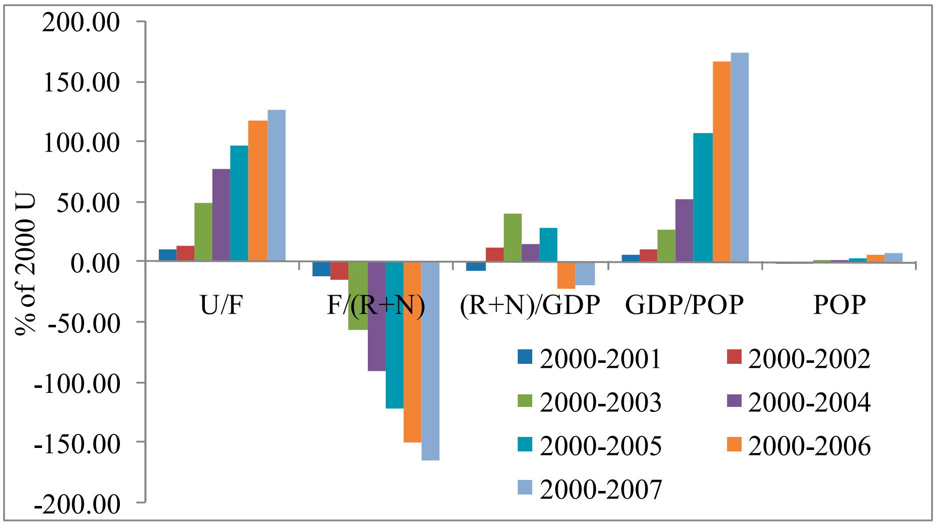
Figure 4. ASA decomposition of the total emergy use (U) in Xifeng during 2000–2007; the contributions of five factors to the percentage of the 2000 total emergy use (U) level.



In Xifeng (Figure 4), the considerable increase in the total emergy use can be seen in the decomposition results as an increase in the GDP/POP, F/(R + N) and POP components, and the economic growth was the main driving force. Since EIR = F/(R + N) indicates the efficiency of external investment in exploiting a unit of local resource, the EIR's contribution to the growth of emergy use means that the social economic system of Xifeng is fragile due to the fact that the local resource basis (R + N) cannot easily be increased and the non-renewable input emergy (N) is mainly contributing to the climate change. The factor (R + N)/GDP contributed to the decrease of emergy use considerably. The U/F factor slightly decreased in the investigated period.

In Qingcheng (Figure 5), the factors GDP/POP and U/F were the main contributors to the increase in total emergy use; while the factor F/(R + N) has decreased the emergy use. However, the factor (R + N)/GDP, unlike Qingyang and Xifeng, was fluctuating to a large extent, while finally decreasing.

Figure 5. ASA decomposition of the total emergy use (U) in Qingcheng during 2000–2007, contributions of five factors to the percentage of the 2000 total emergy use (U) level.



For Zhengning (Figure 6), the decomposition result indicates that GDP/POP was the main driver of the emergy use increase, but (R + N)/GDP contributed to the decrease in emergy use. The U/F factor slightly decreased, except in the second period. Inversely, the F/(R + N) factor slightly increased, except in the third period.

In Ningxian (Figure 7), the factors F/(R + N) and GDP/POP were the main driving forces of the increase in total emergy use, and the contribution of F/(R + N) was more stable. The considerable and steady contribution of F/(R + N) to the U growth refers to the fact that the social economic system of Ningxian is more fragile than Xifeng, and an appropriate policy would be to optimize natural resource use (e.g., convert solar radiation into photovoltaic electricity to replace fossil fuels, recycling waste material resources to replace new raw imports, recycling water after appropriate treatment, *etc.*). The EIR (U/F) and resource utilization rate ((R + N)/GDP) have been the major factors decreasing emergy use. The effect of population scale is smaller than other factors.

Figure 6. ASA decomposition of the total emergy use (U) in Zhengning during 2000–2007; the contributions of five factors to the percentage of the 2000 total emergy use (U) level.

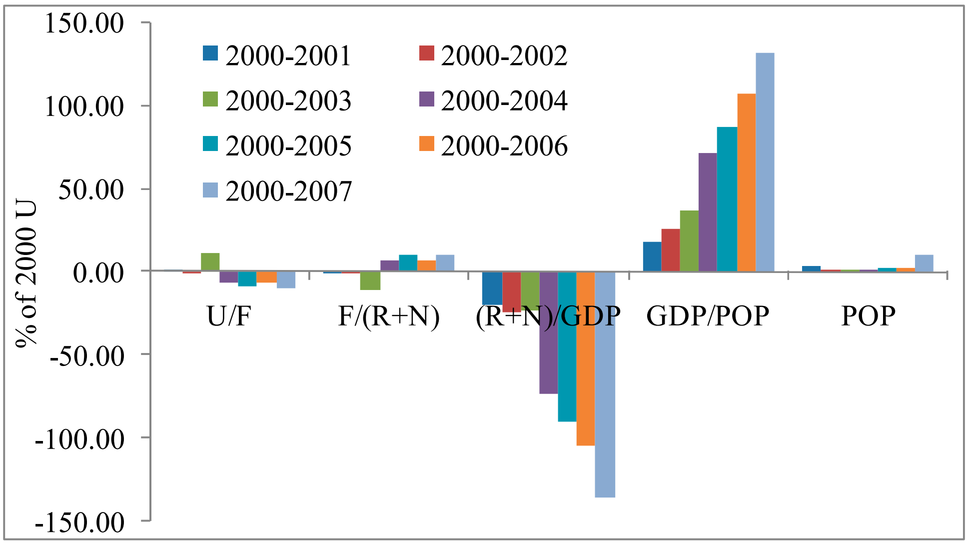
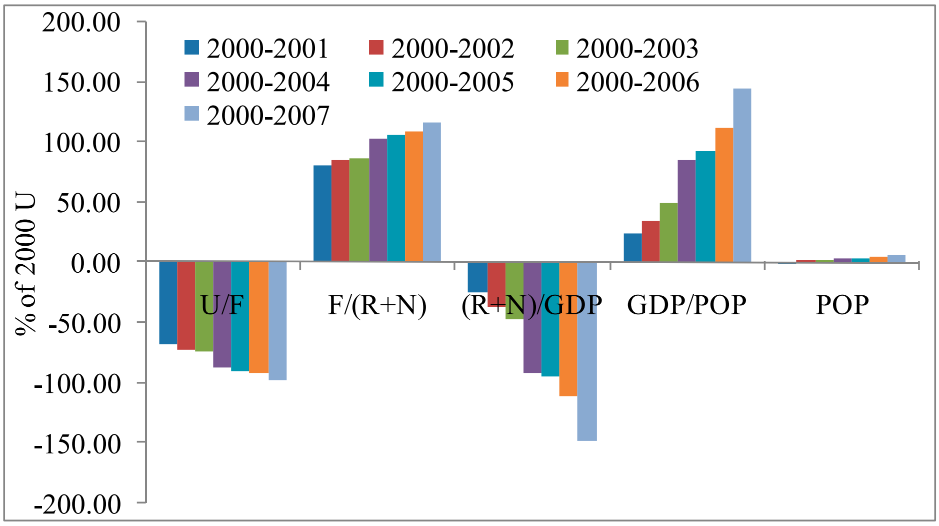
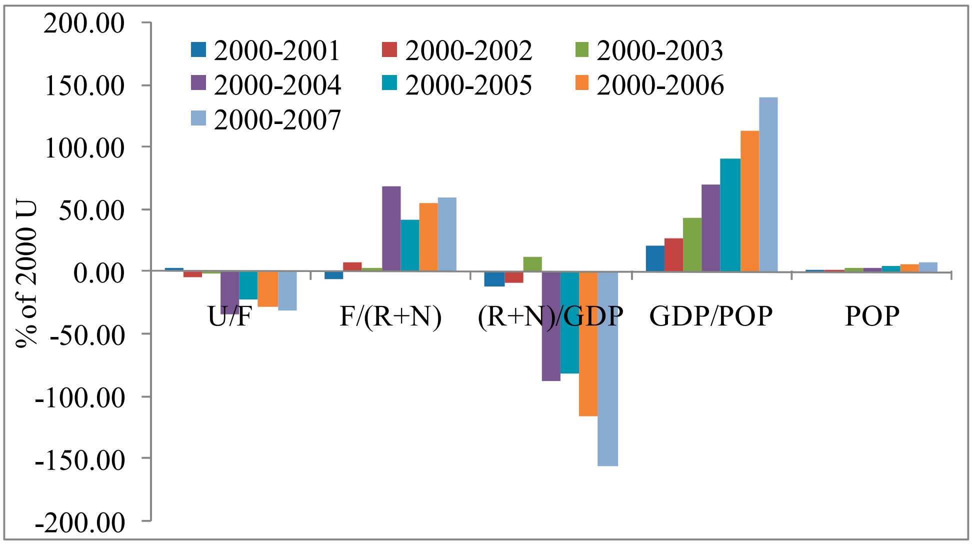


Figure 7. ASA decomposition of the total emergy use (U) in Ningxian during 2000–2007; the contributions of five factors to the percentage of the 2000 total emergy use (U) level.



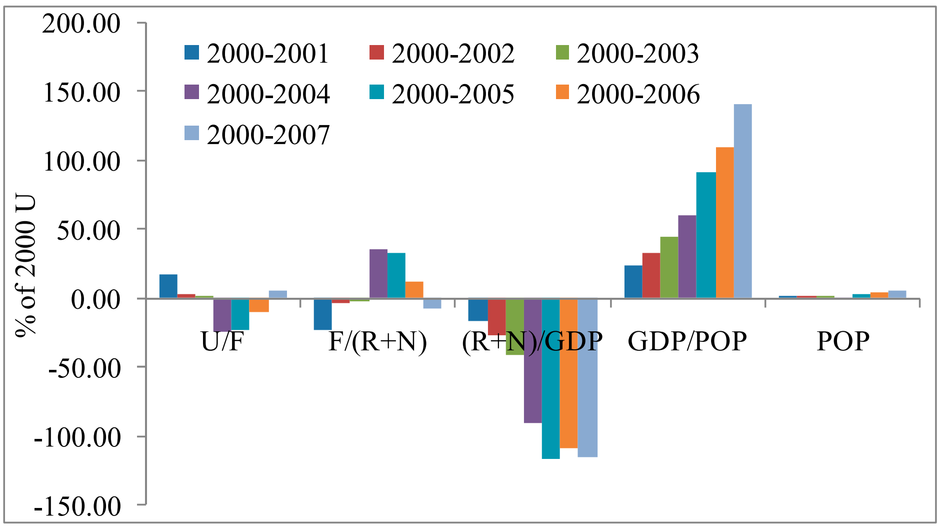
In Zhenyuan (Figure 8), the fast economic growth (GDP/POP) was the most important factor contributing to the emergy use increase, due to its energetic economic development (Table 3). The factor F/(R + N) also has increased emergy use, which suggests policies to optimize natural resource use, but the effect is less than the economic growth. The factor (R + N)/GDP has decreased the emergy use, except in the third period, and the U/F also had negative effects on the emergy use increase, except in the first period.

Figure 8. ASA decomposition of the total emergy use (U) in Zhenyuan during 2000–2007; contributions of five factors to the percentage of the 2000 total emergy use (U) level.



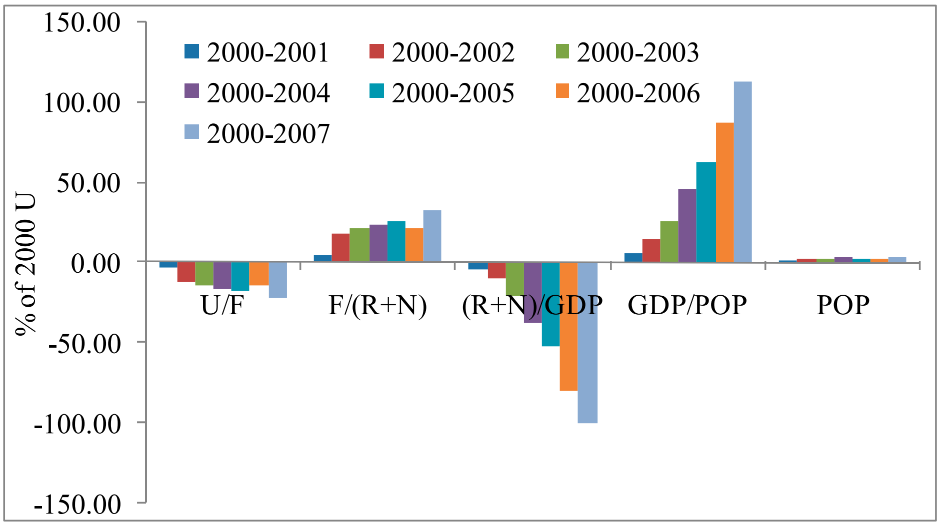
The economic growth in Huanxian (Figure 9) has increased the emergy use. However, the improvement of resource utilization efficiency has decreased the emergy use. The behavior of U/F and F/(R + N) was a bit more complex. For the factor U/F, from 2000 to 2003, the emergy yield ratio (EYR) increased, and after 2003, the parameter shows instead a decline, except in the last year. The factor F/(R + N) shows an inverse behavior.

Figure 9. ASA decomposition of the total emergy use (U) in Huanxian during 2000–2007; contributions of five factors to the percentage of the 2000 total emergy use (U) level.



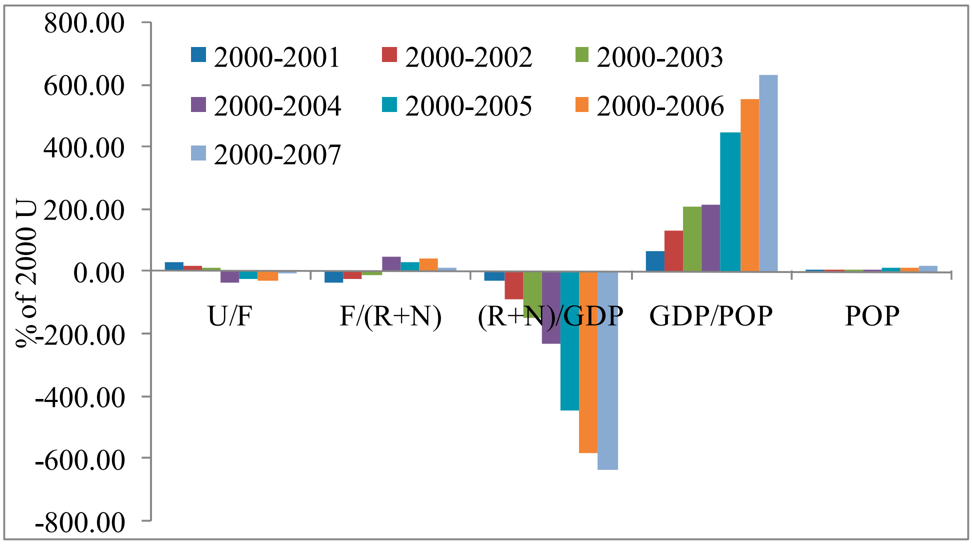
In Heshui (Figure 10), economic growth was the main driving factor of the emergy use increase, and the increase of F/(R + N) contributed to the increase of the total emergy use, although to a lesser extent than GDP/POP. However, the factor (R + N)/GDP showed a steady decline (less natural emergy input per unit of GDP), which strongly contributed to the decrease of the emergy use in the investigated period. The decreasing of U/F contributed to the decease of the total emergy use, but to a lesser extent than (R + N)/GDP.

Figure 10. ASA decomposition of the total emergy use (U) in Heshui during 2000–2007; the contributions of five factors to the percentage of the 2000 total emergy use (U) level.



In Huachi (Figure 11), the factors GDP/POP and (R + N)/GDP, respectively, contributed to increasing and decreasing total emergy use. The factors U/F and F/(R + N) slightly changed in the investigated period. The factor U/F increased before 2003, but after 2003, the parameter showed instead a decline. Inversely, the factor F/(R + N) decreased before 2003, but after 2003, the parameter showed instead an ascent.

Figure 11. ASA decomposition of the total emergy use (U) in Huachi during 2000–2007; the contributions of five factors to the percentage of the 2000 total emergy use (U) level.



5. Summary and Conclusions

The main purpose of this study is to investigate metabolic structure and efficiency and, further to identify driving factors, so that we can employ an emergy-based analysis of the socio-economic metabolism of Qingyang city over 2000–2007 by combining data envelopment analysis (DEA) and decomposition analysis. By integrating emergy accounting into the DEA framework, the paper quantified the ecological efficiency of the socio-economic metabolic system, which can be applied to express the potential efficiency improvement and to make comparisons across different regions. The use of a multi-method analysis helps to avoid misleading interpretations based only on emergy-based indicators.

The investigated regional socio-economic metabolism greatly relied on non-renewable emergy flows and feedback (purchased) emergy flows, except Huanxian and Huachi, which highly depended on renewable emergy flow. Analysis of emerge indicators for sub-regions in Qingyang shows that Qingcheng, with the highest NEYR (35.9), is the main energy supplier in Qingyang, followed by Zhengning (14.24), Ningxian (12.66) and Huanxian (11.37). However, the ELR value of Qingcheng (5.2), which was above the Qingyang average (3.25), indicates that the current economic activities are not sustainable, as they relied mainly on local non-renewable emergy inputs. The highest EIR (29.87) and ELR (35.68) of Xifeng refer to the fact that the region relied more on purchased inputs than locally-available resources, and the region's current economic model has led to great environmental pressure. The ELRs of the other five regions indicate that these regions achieved a balance between the emergy use of renewable and non-renewable resources. The ESI results indicate that Xifeng developed a "consumer"-oriented economy; Ningxian, Qingcheng, Zhenyuan, Heshui and Zhengning developed "producer"-oriented economies; and Huanxian and Huachi were economically behind, and their economic development needs to be accelerated and strengthened.

The emergy-based data envelopment analysis showed that the eight sub-regions, on average, had an EE level of 0.728 in 2007, which implies that Qingyang as a whole has the potential to reduce natural resource inputs and waste output. The EE scores (1.00) of Zhenyuan, Huanxian and Qingcheng indicate that the three regions can be considered as relatively emergy-efficient areas. The EE scores of Xifeng and Heshui are the lowest in Qingyang, and the scores in 2007 were 0.198 and 0.252, which suggest that the two regions could reduce natural resource consumption and waste emission to a great extent without scarifying any desirable output. The ecological efficiency of Zhengning, Ningxian and Huachi is higher than the average level of the whole of Qingyang. During the investigated period, the economic growth was the main driving factor of the increase in the total emergy use in Qingyang and its sub-regions. The contribution of the population scale factor is very small. The factor (R + N)/GDP contributed to the decrease of emergy use considerably (except Qingcheng), which suggests policies to promote the efficiency of resource utilization and, thus, to decrease emergy use further. The positive contribution of the environmental investment ratio to the growth of total emergy use in Xifeng, Zhengning, Ningxian, Zhenyuan, Huanxian, Heshui and Huachi demonstrates that the social economic system of the above seven regions is fragile, especially for Ningxian, Zhenyuan and Heshui.

The integrated approach used in this study is suggested as a tool to design future scenarios of resource use and ecological efficiency in the near future. The results of socio-economic metabolism analysis in Qingyang suggest policies to promote the efficiency of resource utilization, especially for Xifeng and Qingcheng. The fragile social economic systems of Xifeng, Ningxian, Zhenyuan, Heshui and Huachi suggest that series appropriate policies should be adopted to optimize natural resource use (e.g., convert solar radiation into photovoltaic electricity to replace fossil fuels, recycling waste material resources to replace new raw imports, recycling water after appropriate treatment, *etc.*).

It is worth noting that we cannot probe the structures of socio-economic metabolism that are regarded as crucial for policy makers to coordinate the system and improve regional eco-efficiency, because of insufficient statistical data in this economically lagging area. In addition, we employed the uniformed transformity of natural resources, products and processes, which may lead to estimation bias of the regional features to a certain extent. Nevertheless, we believe our findings provide solid and meaningful results that can provide useful implications for policy makers.

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Author Contributions

Zilong Zhang and Xingpeng Chen conceived and designed the study; Zilong Zhang contributed to data collection, data processing and draft paper as well as paper revised; Peter Heck contributed to data analysis and paper revised.

Conflicts of Interest

The authors declare no conflict of interest.

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