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Comparative Analysis for the Urban Metabolic Differences of Two Types of Cities in the Resource-Dependent Region Based on Emergy Theory

Chang Liu, Xueyi Shi *, Lulu Qu and Bingyi Li

College of Land Science and Technology, China University of Geosciences, Beijing 100083, China; 2012140030@edu.cn (C.L.); qululu91@163.com (L.Q.); libingyi0314@163.com (B.L.)

* Correspondence: shixueyi60@163.com; Tel.: +86-10-8232-1363

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Abstract: Urban metabolism analysis has become a useful and effective tool to explore urban socio-economic processes. In this research, in order to explore the similarities and differences of metabolic characteristics and variation rules of different types of resource-dependent cities, we selected two cities—Taiyuan and Jincheng, the capital and a traditional resource-dependent city of Shanxi province, respectively, as research subjects, we also established an urban metabolic evaluation framework by employing a set of eight emergy-based indicators from socio-economic data from 2007 to 2014, and compared the similarities and discrepancies from the perspectives of metabolic structure, intensity, pressure, and efficiency, and put forward some suggestions for pursuing sustainable development for both cities and pointed out that more types of resource-dependent cities should be incorporated in future research work.

Keywords: urban metabolism; resource-dependent city; emergy theory; comparison analysis

1. Introduction

Urban areas are spatial systems in which population, economy, science, technology, culture, resources, and environment are integrated [1]. The urban system involves various socio-economic and environmental processes through material and energy input, absorption, production, transition and output. With the accelerated development of urbanization and industrialization, cities begin to confront serious ecological and environmental problems, such as resource depletion, ecologic environment degradation caused by intensive human activities [2]. Thus, it is essential, and of tremendous significance, to research the features of metabolisms of cities and to try to find ways to enhance the prosperity and sustainability of cities.

Metabolism is a fundamental process in biological sciences, and was first introduced into urban studies by Wolman (1965) [3]. It has been defined as “the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste” [4,5]. Urban metabolism concentrates on the evolution of the urban system, and it gives insights into the co-evolution of metabolic components, and coexistence with the global web of other cities. Thus, research on urban metabolism has a significant role in exploring issues of urban sustainability and helps city managers to make decisions on urban planning [6]. In recent years, many scholars have selected some cities as research subjects, to probe deeply into urban metabolisms regarding socio-economic processes and characteristics to depict the development structure and pattern of a city; some are focused on the metropolitan cities like Beijing, Taipei, Rome and Curitiba [7–10]. There are some researchers who concentrate on specific types of cities, such as Suzhou, an export-oriented city in

Eastern China [11], and Shenyang, an industrial city in the northeast of China. Moreover, there is also research on the regional differences of urban metabolism within a city or a region, such as the research on the spatial disparity between built-up urban sprawl region and urban footprint regions of Xiamen [12], and discussions of each of municipality in the province of Siena [13]. It is concluded that existing research rarely discusses the urban metabolisms of resource-dependent cities, and, in previous research, there are some researchers who use the emergy method to analyze the development of resource-dependent cities, and the works are mainly focused on the development level of a circular economy [14], eco-efficiency [15], evaluation of economic system [16], and urban development level evaluation [17], but there is little research on the urban metabolisms of resource-dependent cities [18], especially of cities located in Shanxi Province of Western China. Shanxi Province has been determined as the "Experimental area of comprehensive reform of resource-dependent economy", and there are few papers related to the comparative analysis of the metabolisms of different types of cities [19]. Resource-dependent cities are cities that heavily rely on the exploitation and utilization of natural resources to stimulate their economic development, urbanization, and industrialization [20,21]. These resource-dependent cities possess characteristics, are higher energy consumed, are heavier polluted, have a higher waste emission, and are more ecologically and environmentally fragile than other cities [22]. Currently, they are facing severe challenges due to the transitions in China; with the price of mineral resource dropping, these cities are in an economic recession and are eager to find ways to rid themselves of this plight.

In this paper, we selected two different types of resource-dependent cities in Shanxi Province: Jincheng and Taiyuan. Jincheng is a traditional, resource-dependent city, which is listed as a mature resource-dependent city in the "Sustainable National Planning of Resource-dependent Cities (2013–2020)". Taiyuan, the capital of Shanxi Province, has been oriented as one of the major centers in China for energy production and for chemical and metallurgical industries, and the proportion of heavy metal industries in Taiyuan is ranked second out of 20 major metropolitans in China [23,24]. The emergy analysis methodology was utilized to probe the temporal dynamic rules of urban metabolisms of these two cities, from 2007 to 2014, and comparisons were made between them to find the similarities and differences, thus, providing some useful suggestions for future strategies for resource-dependent cities and to fill the academic gap in the field.

2. Materials and Methods

2.1. Research Area

Taiyuan city, the capital of Shanxi Province, is located in the central part of Shanxi province, with a total area amounting to 6988 km^2. Up to 2014, the total population was 42,989,000 and the urbanization rate reached 85% (the percentage of urban population accounted for the whole population of the city). As a resource-dependent city center in the hinterlands, there are abundant mineral resources, such as iron, manganese, copper, aluminum, lead, zinc, etc., and the heavy metal industry there is extremely developed. The economy has been increasing steadily in recent years, and the value of GDP has almost doubled from 2007 to 2014, increasing from 129.177 billion yuan to 253.109 billion yuan. In 2014, the percentage of value-added by the service industry accounted for 58.47%, while the value-added by the primary and secondary industries was 1.54% and 39.99%, respectively. Overall, the degree of economic agglomeration of Taiyuan was relatively higher and its economic scale gradually expanded, resulting in more resources being consumed, which added a burden to city operation and management.

Jincheng is a traditional mineral-resource-dependent city in the southeastern part of Shanxi Province, and has a reputation for being "the town of iron and steel". The total area is 9490 km^2 and the population was 2.1931 million in 2014. Jincheng is famous for being rich in natural mineral resources, and there are various types of natural resources underground, from the north to the south, such as coal, coalbed methane (CBM), iron ore, and bauxite, which can potentially be exploited and utilized. Jincheng is located in the southern part of the Qinshui Coal Field, and there are several gigantic coal fields, Yonghong Coal Mine, Yong'an Coal Mine, Sihe Coal Mine, etc. Additionally, several enormous mineral resource-related corporations, such as the Jinmei Corporation and the Orchid Corporation are in charge of the exploration of the resources, which play a pivotal role in the prosperity of the city. By the end of 2014, the gross domestic product of the mineral industry reached 53.54 billion yuan, accounting for 73.2% of the GDP of the entire city. The exploration and operation of the local mineral resources promotes tremendously to the socio-economic development and prosperity of the city.

Overall, the exploitation and development of natural resources are the backbone of a city's economic and social prosperity, and the proportion of heavy industry production values within the secondary industry in both cities were above 90% from 2005 to 2014. While Taiyuan serves as the capital of Shanxi Province, not only taking responsibility for enhancing economic and social development, but also operating the administration services and functions and it has great attraction force. Its resource endowment, urban orientation, economic and population scopes, and future development trends have several differences from those of traditional resource-dependent cities, such as Jincheng, in Shanxi Province, thus, it is significant to do a comparative analysis between these two different types of cities in Shanxi Province, which is a heavily resource-dependent region.

2.2. Data Source

The original research data were derived from Taiyuan Statistics Yearbook (2007–2015) [25], and Jincheng Statistics Yearbook (2007–2015) [26].

2.3. Emergy Analysis

Emergy was first introduced by the ecologist Odum, and is defined as the amount of energy of one type (usually solar) that is directly or indirectly required to provide a given flow or storage of energy or matter. Emergy synthesis projects local input flows on a biosphere scale, by converting all the materials, energy sources, human labor, and services required, directly and indirectly, into emergy units that are summed up to yield the total emergy [27,28]. The emergy of all inputs to a system is calculated in terms of solar emjoules (sej) by means of suitable conversion factors called transformities (expressed in sej/J) or specific emergy (expressed in sej/g-or other units). Emergy analysis has been widely applied in recent years to study the socio-economic-environmental metabolism of many cities, e.g., Campania in Italy [29], Beijing [30], Baotou [31], and Chinese capital cities [32]. In this paper, the following steps were used to conduct the emergy analysis:

(1) Analyze the main ingredients and energy flows of the urban metabolism of the research area, and establish a basic database consisting of the natural environment, agriculture, industry, and other economic and social sectors.
(2) Make an emergy analysis diagram and define the system boundary, make a list of input sources and output sources, and then calculate the emergy value in terms of solar emjoules (sej) by the process of conversion. The conversion equation is as follows:

$$E_m = \sum_i T_i \times E_i$$

In the equation: T_i stands for the solar transformity of the ith input flow, while E_i is the actual energy content of the input flow to the process [33].

In this paper, the urban metabolism system is comprised of renewable resources (R), non-renewable resources (N), imported resources (IM), wastes (W), and exported resources (EX). Renewable resources include natural energy, such as solar energy, wind energy, rainfall energy (chemical), rainfall energy (geo-potential), planet cycle energy, and local renewable resources, such as agricultural products, livestock, and aquatic products. Non-renewable resources include electricity, cement, steel, gasoline diesel, etc. The imported and exported resources mainly consist of raw and commercial products, and tourism is also included in the imported resources. The wastes were divided into three parts: Solid wastes, waste water, and waste gas. The values of solar transformity are drawn from published research, by researchers including Odum and Huang [8,34–36]. The details of the composition and structure of the urban metabolism system, and values of solar transformity of each item, are shown in Table 1.

Table 1. Emergy items and urban metabolism and emergy tranformity.

Emergy Category	Item	Unit	Tranformity (sej/J)	Reference
Renewable resource emergy (R)	Solar energy	J	1	[34]
	Wind Energy	J	2.45×10^3	[35]
	Rainfall energy(chemical)	J	3.05×10^4	[35]
	Rainfall energy(geo-potential)	J	4.70×10^4	[35]
	Earth cycle energy	J	5.80×10^4	[35]
	Agricultural products	g	4.08×10^{11}	[34]
	Livestock	g	2.50×10^{11}	[34]
	Aquatic products	g	3.02×10^{10}	[34]
Non-renewable resource emergy (N)	Losses of topsoil	t	1.71×10^3	[35]
	Electricity	J	2.69×10^5	[34]
	Steel	g	3.02×10^9	[34]
	Raw coal	J	6.72×10^4	[34]
	Petroleum	J	1.86×10^5	[34]
	Diesel	J	1.86×10^5	[34]
	Natural gas	J	8.06×10^4	[34]
	Fuel oil	J	6.25×10^4	[35]
	Chemical fertilizer	t	8.28×10^6	[36]
Imported emergy (IM)	Goods income	$	9.37×10^{12}	[35]
	Toursim income	$	1.66×10^{12}	[36]
Exported emergy (EX)	Goods and service income	$	6.34×10^{12}	[35]
Waste emergy (W)	Solid waste	g	1.80×10^9	[8]
	Waste water	g	6.66×10^8	[8]
	Waste air	g	6.66×10^8	[8]

Note: RMB is transformed into US $ using the annual exchange rate from 2007 to 2014.

(3) mergy evaluation indicators were selected to reflect the characteristics and metabolic structure, intensity, pressure, and efficiency of the urban system, based on published papers from Odum, Song and Brown [34,37,38].

According to the paper, the emergy indicator system can be divided into four categories and eight emergy indicators, which are used to gauge the environmental pressure, economic level, and sustainability level of a city. Details of the structure and the composition of the evaluation system, and explanations of each indicator, can be seen in Table 2.

Table 2. Emergy-based indicator system for urban metabolic analysis.

Metabolic Category	Emergy Indicators	Unit	Formula	Explanation
Metabolic emergy structure	Total emergy per year (U)	Sej	R+ N + IM	Total emergy (the export and waste are not included)
	Emergy extroversion ratio (EER)	1	(IM + EX)/ (U + EX + W)	The dependency degree to the import and export of the urban system
Metabolic intensity	Emergy money ratio (EMR)	sej/yuan	U/GDP	Emergy flux produced per unit of economic output
	Emergy per capita (EP)	sej/cap	U/Population	Metabolic efficiency per capita
Metabolic pressure	Environmental loading ratio (ELR)	1	(N + IM)/R	Metabolic system's pressure on the environment
	Emergy waste ratio (EWR)	1	W/R	The circulation power of the urban system
Metabolic efficiency	Emergy yield ratio (EYR)	1	(R + N + IM)/IM	The capacity of resource output of the urban system
	Emergy sustainable index (ESI)	1	EYR/ELR	The sustainability capacity of the local urban system

3. Results

3.1. Metabolic Emergy Structure

In the composition and structure of an urban metabolism, the values of total emergy per year (U) demonstrate an upward trend, but there are no significantly increased amplitudes for Taiyuan and Jincheng. From 2007 to 2014, U of Taiyuan increased from 9.024×10^{23} sej to 9.116×10^{23} sej, which is much higher than the U of Jincheng, which increased from 5.147×10^{23} sej to 6.422×10^{23} sej (Figure 1). However, in terms of a growth range, the value of total emergy in Jincheng rose by 24.76%, while Taiyuan's U increased by only 1.02% over the same period. These results show that the materials and energy involved in both cities increased due to an accelerated development of urbanization and industrialization in recent years, but because the entire scale of Taiyuan is too large, the potential rising speed was slowed. More specifically, N increased dramatically from 1.203×10^{23} sej in 2007 to 1.567×10^{23} sej in 2014 in Jincheng, while, over the same period, the figure for Taiyuan decreased from 1.166×10^{23} sej, in 2007, to 0.741×10^{23} sej, in 2014. Jincheng is abundant in mineral resources and it has a very high energy-resource self-sufficiency rate, so the city develops its economy mainly through exploiting and producing mineral resources, which are generally non-renewable. However, as for Taiyuan, its economic development pattern mainly relies on importing and exporting resources and services. As illustrated in Figure 2, Taiyuan's emergy extroversion ratio (EER) experienced a continuous increase from 2007 to 2014, and its value was higher than that of Jincheng. The EER for Taiyuan was 0.076 in 2007, and amounted to 0.142 in 2014, with an average value of 0.105, while EER for Jincheng was 0.018 in 2007, and peaked at 0.094 in 2014, with an average value of 0.054.

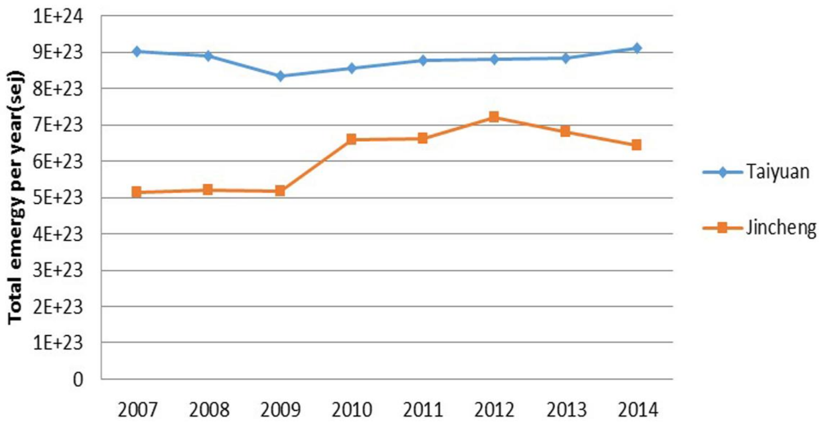

Figure 1. Time series for values of total emergy per year for Taiyuan and Jincheng.

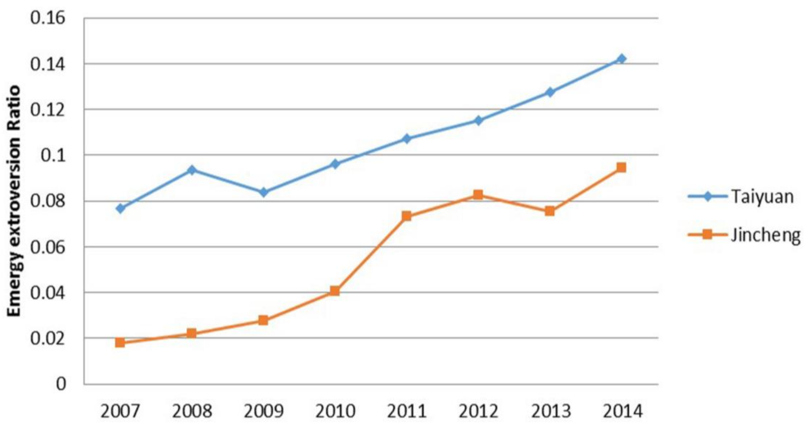

Figure 2. Time series for values of emergy extroversion ratio for Taiyuan and Jincheng.

3.2. Metabolic Intensity

Emergy money ratio (EMR) and emergy per capita (EP) are incorporated to represent metabolic intensity. Through measuring the values of EMR, the purchasing power of the currency to obtain resource emergy for a city can be shown. The higher the value of EMR is, the fewer resources are being used to generate the same amount of GDP. On the whole, the EMR in both cities showed a declining trend, with Taiyuan's EMR reduced from 5.31×10^{13} sej/$ in 2007 to 2.74×10^{13} sej/$ in 2014, and Jincheng's EMR dropping from 8.90×10^{13} sej/$ in 2007 to 4.71×10^{13} sej/$ in 2014 (Figure 3). It shows that the emergy obtained by per unit of economic output in Jincheng was higher than that of Taiyuan, and the increasing speed of consuming resource and energy was faster than the increase of GDP. EP reflects the possession of disposable resources per person in an urban metabolism system, which is an indicator used to measure the potential average living standards of a population. From 2007 to 2014, EP for Taiyuan remained at the level of approximately 2.42×10^{17} sej/cap; however, Jincheng's EP showed an upward trend, increasing from 2.40×10^{17} sej/cap in 2007, peaking at 3.29×10^{17} sej/cap in 2012, and declining to 2.93×10^{17} sej/cap in 2014 (Figure 4). It could be concluded that, in recent years, the level of EP in Jincheng is higher than that of Taiyuan, and the increasing growth of population has been lagging behind that of available resources and the energy increment in Jincheng. However, for Taiyuan, the trend is different, due to the fact that an increasing number of workers and trained staff from neighboring cities pour into Taiyuan, as there are more employment opportunities and better living standards. Thus, the larger scale of the population made EP lower.

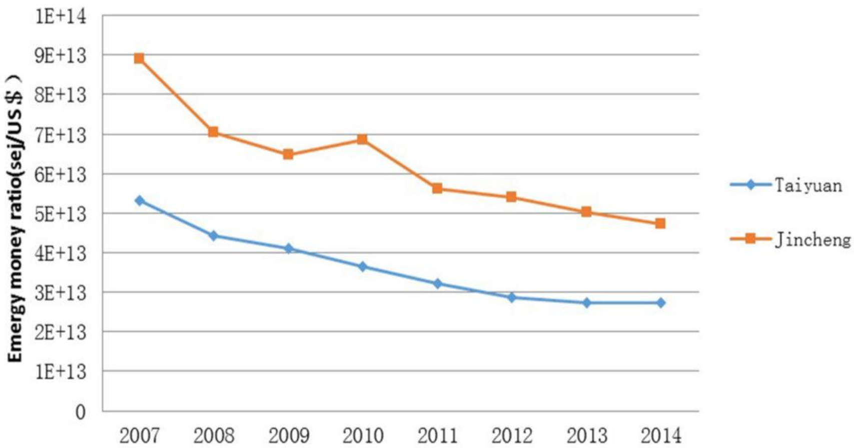

Figure 3. Time series for values of emergy money ratio for Taiyuan and Jincheng.

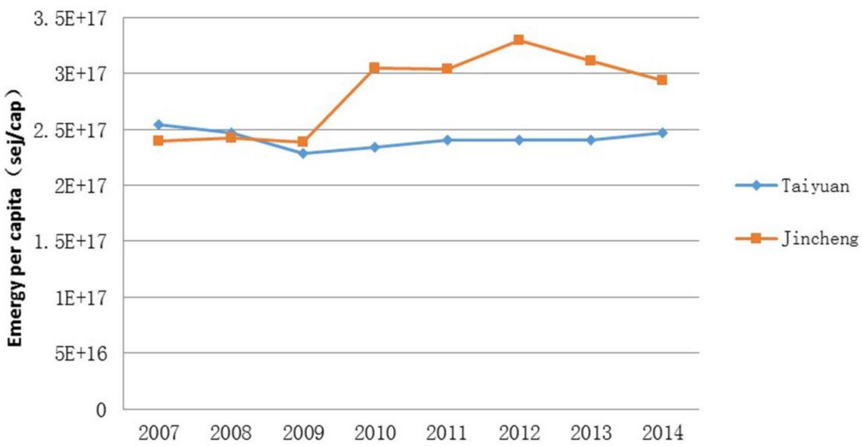

Figure 4. Time series for values of emergy per capita for Taiyuan and Jincheng.

3.3. Metabolic Pressure

The metabolic pressure was composed of the environmental loading ratio (ELR) and emergy waste ratio (EWR). ELR indicated the pressure that the system placed on its environment, which could be considered a measure of metabolic system stress. For both cities, ELRs were on the rise with some fluctuations. On average, Jincheng's ELR was higher than that of Taiyuan. From 2007 to 2014, ELR in Jincheng escalated from 0.350 to 0.590, while, during the same period, Taiyuan's ELR had rose slightly, from 0.236 to 0.272 (Figure 5). The above results demonstrate that the heavy burden of the use of non-renewable resources in Jincheng exerted more stress on the urban system than in Taiyuan, and there exists a great deal of potential opportunity for Jincheng to adjust its industrial structure and to implement an energy saving strategy. Contrary to ELR, Taiyuan's EWR rose from 0.152 in 2007 to 0.265 in 2014, due to fact that the waste emergy increased, while the renewable resource emergy decreased; however, Jincheng's EWR increased from 0.152 in 2007 to 0.265 in 2014, but the average level of EWR in Taiyuan was much lower than that of Jincheng (Figure 6). These results indicate that Jincheng has functions for exploiting and producing mineral resources and other non-renewable resources, and that the discharge of massive amounts of waste is inevitable, but the overall declining trend of EWR in Jincheng shows that the city takes some measures to integrate mineral resources and to develop a circular economy to curb the quantity of waste that is caused by mineral resource production [39]. As Taiyuan's urban scale is much larger than that of Jincheng, and owing to the accelerated development of urbanization in Taiyuan, more and more waste is produced and discharged.

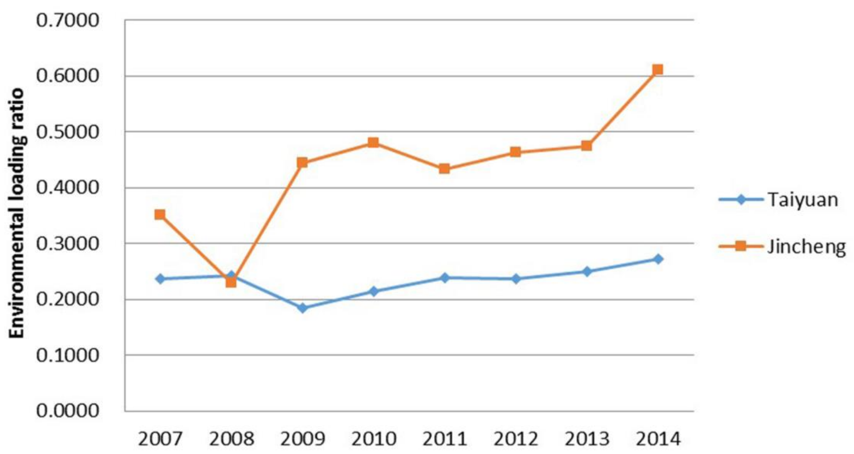

Figure 5. Time series for values of environmental loading ratio for Taiyuan and Jincheng.

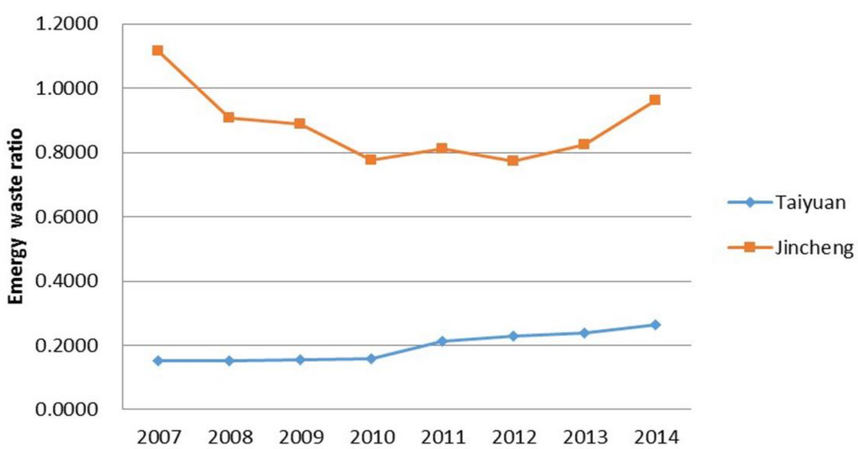

Figure 6. Time series for values of emergy waste ratio for Taiyuan and Jincheng.

3.4. Metabolic Efficiency

Metabolic efficiency is used to reflect the output capacity of input resources in an urban metabolic system, which includes emergy yield ratio (EYR) and emergy sustainable index (ESI). EYR measures the investment efficiency of external resources to exploit local resources and contributes to the economy. The higher the value of EYR, the more efficient the energy and materials are used in an urban system. As can be seen in Figure 7, the EYR of both cities decreased gradually from 2007 to 2014, which demonstrates that the utilization efficiency of resources has been decreasing, and the configuration of resources in both cities still need to be optimized. It is particularly noticeable that Jincheng's EYR was higher, but that it dropped sharply, from 39.08 in 2007 to 10.15, in 2011, with an approximate annual decrease of 17.20%. In terms of ESI, the indicator is the ratio of EYR to ELR. A higher value of ESI means that the sustainability of a metabolic process is greater [40]. In recent years, the ESIs of Taiyuan and Jincheng showed a downward tendency, declining to 27.80 and 12.12 in 2014, respectively, which shows that the self-organization and sustainability of both cities were continuously deteriorating [41,42]. In more detail, from 2007 to 2008, Jincheng's ESI was higher than that of Jincheng, and from 2009 to 2014, the ESI of Taiyuan was greater than that of Jincheng (Figure 8). These results reveal that Jincheng, a traditionally resource-dependent city, explored and produced large quantities of mineral resources, which put more stress on the environment as a consequence, and that this was not sustainable in the long run. While for Taiyuan, the capital of Shanxi Province, though tremendous volumes of mineral resources were buried underground the city, its exploration activities were constrained by some influential factors, such as urban land use planning and environmental regulations, etc., so the stress to the environment was relatively low, making its sustainability of the urban metabolism superior to that of Jincheng.

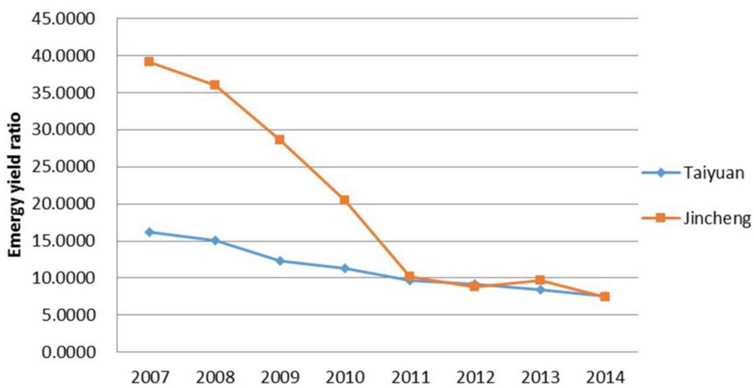

Figure 7. Time series for values of emergy yield ratio for Taiyuan and Jincheng.

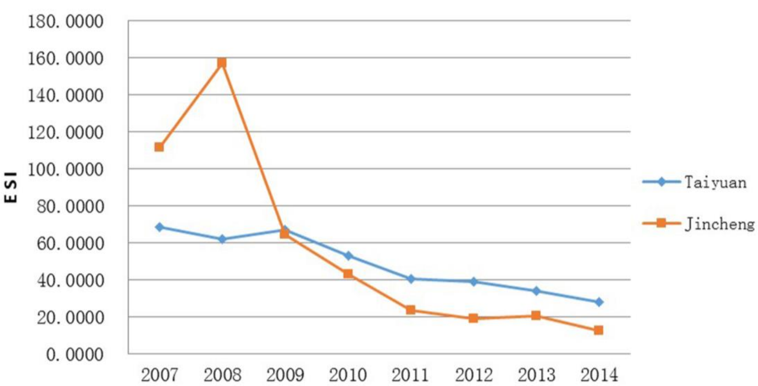

Figure 8. Time series for values of emergy sustainable index for Taiyuan and Jincheng.

4. Discussion

The emergy analysis methodology and comparison analysis provides clear insights into the metabolic features and dynamic development rules of urban systems between two different types of resource-dependent cities. Through this method, we can figure out the differences between the urban metabolic characteristics and development problems, thus providing adequate data, which could offer useful reference for future planning of cities, for planners, engineers, and end users [43]. However, due to the limitations of time and data access, we only conducted a comparison analysis between two cities, thus, in the future, more research samples should be incorporated, and more diverse resource-dependent cities should be included, by conducting comparison analyses to fill in the academic gap.

5. Conclusions and Policy Implications

For this paper, we selected Jincheng and Taiyuan as research subjects, calculated the emergy-based indices by which to evaluate the mechanisms and characteristics of socio-economic development and the urban system, and adopted a comparison analysis methodology to analyze the differences between the two cities. The conclusions were as follows:

From 2007 to 2014, the metabolic systems of Taiyuan and Jincheng underwent dramatic changes, with the acceleration of urban socio-economic development, and there exist several discrepancies from the perspectives of metabolic structure, intensity, pressure, and efficiency between these two cities. In terms of metabolic structure, more non-renewable resources have been exploited and utilized to stimulate urban development in Jincheng, and Taiyuan is more dependent on the resources and services from the outside when compared to Jincheng. From the aspect of metabolic intensity, the economic efficiency of the input resources of both cities were elevated, and an increasing population in Taiyuan resulted in a lower emergy per capita in Taiyuan than in Jincheng. In terms of metabolic pressure, the ELR and EWR of both cities shared a similar rule. Jincheng's ELR and EMR were higher than those of Taiyuan due to the fact that the utilization of mineral resources in Jincheng put a greater stress on the environment. On a temporal scale, Jincheng's ELR and Taiyuan's EMR and EWR increased from 2007 to 2014, which was consistent with the universal rule of urban sprawl and development [44]. However, it was of particular interest that Jincheng's EWR showed an overall downward trend, since Shanxi Province had been encouraging and implementing coal resource integration projects to save energy and reduce waste emissions [45]. Additionally, for metabolic efficiency, EYR and ESI in Taiyuan were higher than in Jincheng, which was mainly because the urbanization level is higher in Taiyuan so that Taiyuan is less dependent on secondary industries, and its service industries account for a larger portion of the economy, indicating that Taiyuan has developed a more mature urban development mode. However, the two indicators for both cities were on the decline, which shows that there are still some obstacles and challenges to enhancing production efficiency, and both cities have confronted the bottleneck of increasing production efficiency and becoming more sustainable.

In addition, we could see that Jincheng's urban development is mainly dependent on the consumption of non-renewable mineral resources, which is likely to aggravate resource depletion and environmental conditions, making it less sustainable with respect to future development. Thus, it is strongly recommended that Jincheng should change its urban development mode, and lessen its consumption of mineral resources and find alternative clean energy to replace the demand for traditional fossil fuels. For Taiyuan, its urban development relies more on imports and its main urban problems, associated with urban development, were low resource utilization efficiency, greater metabolic stress, environmental degradation, etc. Thus, it is suggested that Taiyuan should alter its current development mode and gradually establish an efficient, scientific, and modern production mode, and to continue promoting the development of service industries, make better use of the input resources, and increase its utilization efficiency of the metabolic system.

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