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Article

Analysis of Land-Use Emergy Indicators Based on Urban Metabolism: A Case Study for Beijing

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Abstract: The correlation of urban metabolism and changes in land use is an important issue in urban ecology, but recent research lacks consideration of the mechanisms and interactions between them. In this research, we did an emergy analysis of the flows of materials, energy, and capital within the socioeconomic system of Beijing. We calculated emergy-based evaluation indices of urban metabolism and land use change, to analyze the relationship between urban metabolism and land use by correlation analysis and regression analysis. Results indicate that the socio-economic activities on built-up land depend on local, non-renewable resource exploitation and external resource inputs. The emergy utilization efficiency of farmland has consistently decreased, but there remains significant utilization potential there. Urban development in Beijing relies on production activities on built-up land, which is subjected to great environmental pressure during extraction of material resources. To keep the economy developing effectively, we suggest that Beijing should commit to development of a circular economy, and change the land-use concept to "Smart Growth". In this paper, we efficaciously solve the problem of conflicting measurement units, and avoid the disadvantages of subjective assignment. Consequently, this work provides not only a more scientific way to study land problems, but also provides a reliable reference for ecological construction and economic development in Beijing.

Keywords: urban metabolism; land use; index evaluation; Beijing

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1. Introduction

Urban areas (cities) are spatial systems in which population, economy, science, technology, culture, resources, and environment are integrated [1]. However, they are semi-open ecosystems that, at the same time, must exchange the materials and energy needed to maintain their operation, and eject the wastes they generate to the outside environment. Being a complex organism, a city continuously carries on the metabolic processes needed for its development. Accelerating urbanization and increasing population, accompanied by developing industrialization, can be seen in expanding urban areas. These conditions lead to greater resource consumption and more waste emissions. The typical high input/low output/high pollution extensive-development pattern results in serious urban environmental problems that limit social and economic development [2]. Urban environmental problems mainly exist within the processes of urban metabolism. Taking urban metabolic research as an entry point to analyze every link of urban development is imperative for solving environmental problems and achieving sustainable development.

Since Wolman [3] introduced the concept of "urban metabolism", scholars around the world have done deep research on it. Urban metabolism is the focal point of urban ecology: the analysis of the processes involved in the exchange of materials and energy conversion, as well as their use and disposal. Urban metabolism research integrates multidisciplinary theories and the perspectives of physical geography, biology, ecology, economics, and sociology [4]. The methods currently used include material-flow accounting [5,6], emergy accounting [7], ecological network analysis [8] and ecological footprint accounting [9]. The research scale of urban metabolism varies from regional [10] to national [11], and then down to community [12] and household [13]. In recent years, emergy analysis of the flow of energy, materials, and capital has emerged as a new research field. There are many related cases around the world. Early emergy analysis of urban metabolism focused on accounting for the metabolic emergy of materials, energy and capital. Later, some scholars set up a series of index systems for socio-economic evaluation (e.g., emergy structure, emergy density, *etc.*) [14], and urban development evaluation (e.g., sustainability) [15,16] based on emergy analysis. These were used to evaluate the status of urban development, and to establish dynamic models for an urban metabolic efficiency system [17] by which to study urban transformation. Others combined emergy analysis with sensitivity analysis [18] to find optimal paths for urban development strategy.

Land use is the core issue of theory and practice in the field of urban planning [19], and urban demand for land is essentially the demand for realizing the goal of urban socio-economic development [20]. Current research on urban land use is focused on intensive and sustainable land use, including research on connotation [21], theories [22], evaluation [23], driving forces [24], effects [25], and approaches [26]. Various methods are applied in the research, such as statistical analysis (e.g., multi-factor analysis [27], logistic regression analysis [28], *etc.*), dynamic process model (e.g., cellular automaton [29], agent-based models [30], *etc.*), spatial analysis [31] and lifecycle assessment [32]. There are three kinds of scale in spatiality: macro scale contains a whole country, urban agglomerations, and provinces [33–35], medium scale includes cities and functional regions [36,37], and micro scale refers to parcels [38].

The International Human Dimensions Program on Global Environmental Change (IHPD) lists the discussion between land use change (the most important factor in urban metabolism change) and social metabolism, as the core of plans for global change. The program also emphasized that correlation and impact mechanism analysis should be strengthened [39]. Research on urban metabolism extends over a half century, but most of it only deals with resource consumption and waste generation; the study of interactive relationships between urban metabolism and land use is still in its infancy. In 2006, Xianjin Huang [40] discussed the correlation of land-use intensity and material metabolic flux efficiency in theory. Moreover, the influence mechanism of the land-use-change process (including land use type, intensity, and pattern) on material metabolism was given preliminary analysis. However, it was just a theoretical discussion, lacked specific methods to carry out empirical study. Chunlin Li [41] accumulated asset change of natural areas, agricultural areas, and urban areas from 1971 to 2005, and the temporal dynamics of socio-economic metabolism and land use change was analyzed. The simulation results illustrated that there is an interaction between the development of the socio-economic system and land use change, but no results showed how they influenced each other. Yuqin Wu [42] counted the metabolic emergy of socio-economy and farm land of Guangzhou, and Ricardo [43] used emergy synthesis and emergy-based indicators to assess the sustainability of the residential land use of seven boroughs on the Island of Montreal. Recent research has often merely been focused on the flux of materials and energy, as well as waste emissions. This not only is a single method with no further consideration of the mechanisms and interactions between urban metabolism and land use, but also lacks case studies for comparison.

In this paper, we developed a set of emergy-based indices for evaluating metabolic density, emergy yield ratio, environmental load ratio, and emergy sustainable indices for different types of land. We then attempted to find the interrelations between land-use change and urban metabolism, by correlation analysis and regression analysis. Thus, this work provides an appreciation of the change of metabolism and land use in Beijing, offers new ideas for land administration and urban planning, and provides a frame of reference for solving urban ecological problems.

2. Methodology

2.1. Conceptual Model of an Urban Metabolic System

A city is a complex super-organism with a range of metabolic processes. Materials mined from inside or input from outside will be transformed into material capital by a series of urban socio-economic activities for a period of time, and remains will be converted to waste and released into the environment. The conceptual model is composed of built-up land, farmland, and unused land, according to the sources of energy driving the urban ecological system, as proposed by Odum [44]. Regarding each land type as a socio-economic-ecological subsystem, we analyzed the input and output between subsystems, and established an urban socio-economic system integrated with land use change, as shown in Figure 1.

The inner environment represents the area within the administrative boundary, which provides raw materials, fossil fuels, foods, goods, and services for urban socio-economical activities. However, the inner environment cannot support all the metabolic activities; materials, and energy from outside are also needed to sustain the metabolism. Moreover, wastes and emissions must be released into the outside environment. Thus, the research on urban metabolism should not only focus on production, consumption, and processing of urban internal resources, but should also emphasize the input and output of material and energy between the internal and external environment.

Built-up land—a consumption system—consumes plenty of local resources and material inputs, including raw materials, fossil fuels, foods, goods, and services; and exports goods and services to the outside as well. Farmland is a productive system for which inputs of organic matter and industrial auxiliary materials enable production of agricultural commodities through photosynthesis and other chemical reactions, from which these products are then exported to building areas and to the outside environment.

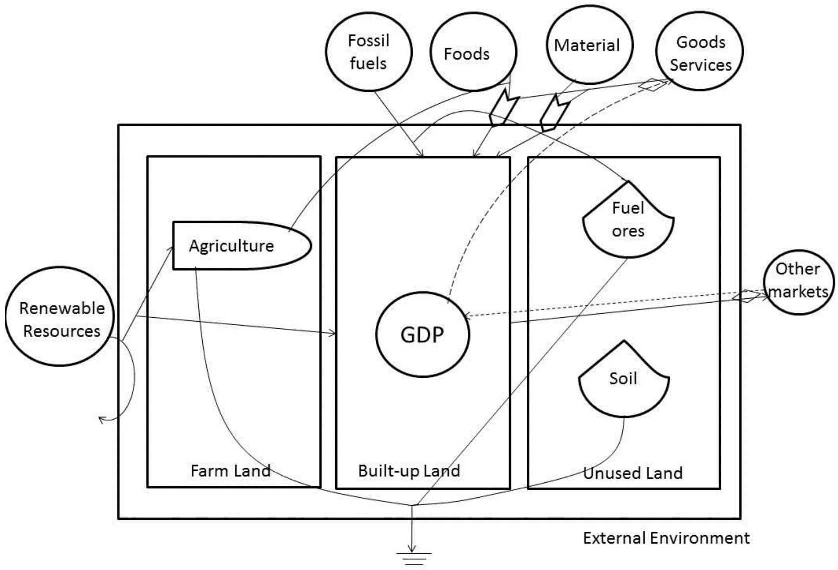


Figure 1. Illustration of an urban socio-economic metabolic system.

2.2. Emergy Accounting

Odum [45] gave a definition of emergy in 1986, seeing it as a measure of one kind of material or energy. Emergy analysis is a method to measure the value or quantity of material or energy (by an objective and uniform metric evaluation criterion—solar emergy) that is used to transform the different natural or human-input flows of material, energy, information, and capital. These are made relative to a uniform measurement standard, by the use of specific conversion factors and by combining socioeconomic with eco-environmental systems, to analyze the flows and transformations of materials and energy quantitatively. The formula [46] is given as:

$$\mathrm{Em} = \tau \mathrm{Ex} \quad (1)$$

Here, Em is the emergy of one material or energy, Ex is the available joules of one material or energy, and τ is the emergy transformity of material or energy, which is the solar emjoules it needed to transform. Transformity of different materials and energy is different, higher transformity means more solar energy consumed to produce one product.

Urban metabolic emergy includes the emergy of renewable resources (R) mainly from sunlight, wind, rain, rivers, and earth cycles, local non-renewable resources (N), imported resources (IMP) and exports (EXP). To avoid repetitive computation, we termed R as the Maximum emergy flow of renewable resources [47]. This is cost-free environmental emergy, coming from sunlight, rain, wind, rivers, and earth cycles. Non-renewable resources include diffuse agricultural resources (N0) such as soil loss, and indigenous fossil fuels (N1) such as fossil fuels and industrial materials. Imports include imported fossil fuels, goods, and services. Exports include goods and services in exports and waste emissions (EW). On the foundation of Huang's [48] research accomplishment, it was determined that the total urban metabolic emergy flows (U) is the sum of local and imported resources, *i.e.*, the sum of R, N, and IMP.

2.3. Emergy-Based Evaluation System of Urban Metabolism

We selected five indices (flux, structures, intensity, efficiency, and waste emission ratio) to evaluate the urban metabolic status, and divided the structures into sub-classes to enable better analysis [49], as shown in Table 1.

Table 1. Emergy indices for evaluating urban metabolism.

Indices		Formula
Flux(F)		U
	S_1	R/(R + N)
Structures	S_2	N/U
	S_3	IMP/U
Intensity(I)		U/population
Efficiency(E)		GDP/U
Waste Emission Ratio(W)		E_W/U

Flux (F) is the sum of materials and energy from the internal system and external environment, which is the sum of emergy input. Structure is the composition of metabolic material and energy: S_1 is the percentage of renewable resources that account for the internal resources; higher values indicate that more renewable resources are consumed in the process of urban development. S_2 is the percentage that nonrenewable resources emergy accounts for, of the total emergy input. S_3 is the percentage that imported resources emergy accounts for, of the total emergy input, and is used to express the level of dependency of urban development on external resources. Intensity (I) is emergy utilization per capita, used to evaluate living standards. Efficiency (E) is the GDP of per unit flux, used to express the utilization rate of resources. The waste emission ratio (w) is the percentage of waste, emission emergy accounts for, of flux.

2.4. Emergy-Based Evaluation of Land Use

To evaluate the metabolic status of farmland, built-up land, as well as the whole urban area, we selected the four indices (metabolic density, emergy yield ratio, land environmental load ratio, and land emergy sustainable indices [50]) in Table 2, and analyzed changes in their values over time.

Table 2. Emergy-based indices for evaluating land use.

Indices	Formula
Metabolic Density(D)	U_i/Land Area
Emergy Yield Ratio(EYR)	Total Land Emergy Output/Total Land Emergy Input
Land Environmental Load Ratio(ELR)	(IMP + N)/R
Land Emergy Sustainable Indices (ESI)	EYR/ELR

Metabolic density (D) is the emergy consumed per land unit; higher values indicate a more prosperous economy, while the land has more metabolic pressure. The emergy yield ratio (EYR) is the ratio of total land emergy output to total land emergy input; higher values indicate that the land emergy utilization is more efficient. The land environmental load ratio (ELR) is the ratio of nonrenewable resources emergy and imported resources emergy, to renewable resources emergy, which is used to indicate land load pressure as a warning. Here, higher values indicate that the land environmental load is higher. Land emergy sustainable indices (ESI) is the ratio of the emergy yield ratio to the land environmental load ratio (*i.e.*, the emergy yield ratio per unit land load pressure); higher values indicate more socioeconomic benefits per unit land-load pressure, and land utilization is more sustainable.

2.5. Correlation Analysis of Urban Metabolism and Land Use Changes

We evaluated the impact of land-use change on urban metabolism from the aspect of land use type and land use intensity.

From the aspect of land-use type, we counted every 2-year increment of emergy use, metabolic density, emergy yield ratio, environmental load ratio, and emergy sustainable indices, of farmland, built-up land, and total urban area. Then we calculated the correlation coefficient of these increments of farmland, built-up land, and urban land, to discuss the influence of land-use change of different types for the quantitative change of urban environmental ratio and emergy sustainability.

Because intensive and compact use is the trend in land utilization, metabolic density would be a very important index to evaluate the land use intensity. From the aspect of land-use intensity, we tried regression fitting of “D” increment of land-use type and ELR increment (ESI increment) of total land with different models, to find the change in variation of emergy indices of urban environmental load and sustainability, with the change of land use intensity.

3. Results

3.1. Emergy-Based Evaluation of the Metabolism of Beijing

We used the data on materials, energy, and capital flows of Beijing from 1996 to 2012, at 2-year intervals, to calculate solar emergy of renewable resources, nonrenewable resources, imports, and outside sources, exports, and wastes. The solar emergy values of each item are shown in Table 3. The raw data used in the emergy calculations are from the Beijing Statistical Year Book [51], China Statistical Year Book on environment [52], China Industry Statistical Year Book [53], China Forestry Statistical Year Book [54], Chinese Rural Statistical Year Book [55], and China Energy Statistical Year Book [56]. The land use data are census data from the Beijing Statistical Year Book [51]. In this analysis, we adopted the 15.83×10^{24} seJ planetary baseline value for annual emergy input [57]. The data of solar transformity are from Liu [15] and Zhang [58].

Table 3. Emergy synthesis for the material metabolism of Beijing from 1996 to 2012.

Item	Solar transformity	Solar emergy ($\times 10^{20}$ seJ)								
		1996	1998	2000	2002	2004	2006	2008	2010	2012
Renewable sources										
1. Sunlight	1	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
2. Wind, kinetic	2.51×10^3	1.41	1.19	1.25	1.19	1.22	1.18	1.18	1.19	1.18
3. Rain, geopotential	1.74×10^4	0.86	0.90	0.45	0.45	0.59	0.39	0.77	0.64	0.90
4. Rain, chemical	3.05×10^4	17.33	18.09	9.18	9.16	11.95	7.86	15.49	12.92	18.13
5. Earth cycle	4.70×10^4	8.74	8.74	8.74	8.74	8.74	8.74	8.74	8.74	8.74
6. Rivers, geopotential	9.73×10^4	5.55	5.55	5.25	4.57	7.01	5.74	11.09	6.23	15.47
Non-renewable sources										
7. Soil losses	1.70×10^7	1.12	1.11	4.58	5.14	5.75	2.15	4.33	1.87	1.91
Indigenous fossil fuels										
8. Coal	6.69×10^4	198.03	194.11	135.29	172.54	209.80	186.27	113.72	98.04	96.07
Indigenous material input										
9. Limestone	1.68×10^9	134.23	157.02	185.25	198.02	271.98	284.78	497.81	234.98	206.82
10. Steel	3.16×10^9	261.96	253.34	253.88	258.15	274.37	258.53	207.55	250.95	91.51
11. Pig iron	1.44×10^9	100.08	108.04	111.35	111.29	115.47	113.44	64.63	59.33	0.00
12. Electricity	1.74×10^5	13.26	17.05	17.05	1.89	1.89	1.89	1.89	5.68	9.47
Imports and outside sources										
13. Agricultural production	1.43×10^5	111.40	113.54	106.65	101.94	115.24	140.97	145.16	158.61	152.85
14. Livestock production	9.15×10^5	62.22	107.97	80.52	93.72	14.55	12.91	20.79	11.97	51.74
15. Fisheries production	3.36×10^6	6.52	32.26	31.01	22.85	17.46	12.50	7.18	9.83	8.40
16. Coal	6.69×10^4	435.28	403.91	462.73	417.63	462.73	550.96	507.82	523.51	447.04
17. Coke	1.10×10^5	56.37	37.58	34.45	31.32	56.37	40.71	25.05	25.05	9.40
18. Crude oil	9.08×10^4	262.70	244.83	288.17	281.33	44.48	480.16	439.48	418.19	409.44
19. Gasoline	1.05×10^5	27.62	30.79	31.70	0.00	0.00	73.81	74.26	93.73	112.75
20. Kerosene	1.10×10^5	51.71	54.08	74.95	83.49	115.74	131.87	185.48	198.76	231.02
21. Diesel	1.10×10^5	20.20	10.80	26.78	0.00	66.24	69.99	77.04	82.68	85.03
22. Fuel oil	1.10×10^5	40.53	14.74	8.29	5.53	8.29	6.91	14.74	30.86	37.30
23. Liquefied petroleum gas	1.11×10^5	0.00	0.00	0.00	0.00	4.46	6.69	12.83	7.81	7.81
24. Natural gas	9.85×10^5	5.75	14.57	42.08	78.55	103.56	147.21	232.58	287.78	354.71

Table 3. *Cont.*

Item	Solar transformity	Solar emergy (×10^20^ seJ)								
		1996	**1998**	**2000**	**2002**	**2004**	**2006**	**2008**	**2010**	**2012**
Exports										
25. Chemical fertilizer	2.67×10^{7}	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04
26. Plastic	5.39×10^{9}	0.63	0.52	0.53	0.67	0.53	0.59	0.77	0.73	0.72
27. Pesticides	2.49×10^{10}	2.85	1.27	1.35	1.17	1.33	1.16	0.96	0.99	0.98
28. Electricity	1.74×10^{5}	269.07	318.34	377.08	488.87	587.41	678.36	875.43	1072.49	1184.29
29. Goods in imports	5.00×10^{12}	1059.95	999.65	1871.55	1994.55	3700.30	6004.15	10,712.90	12,311.10	17,423.75
30. Services in imports	5.00×10^{12}	118.77	176.19	333.38	547.09	922.19	1493.96	2537.40	4298.47	7359.51
31. Foreign investment	4.00×10^{12}	6.88	8.67	6.74	7.17	12.34	18.21	24.33	25.46	32.17
32. Agricultural production	1.43×10^{5}	7.31	10.83	6.22	6.10	4.62	1.73	1.95	15.85	10.70
33. Livestock production	9.15×10^{5}	3.78	1.17	1.85	0.35	0.43	0.33	0.23	0.26	0.08
34. Fisheries production	3.36×10^{6}	1.44	3.12	4.84	5.48	6.55	2.53	1.80	1.97	1.68
35. Coal	6.69×10^{4}	103.92	84.31	84.31	101.96	107.84	137.25	105.88	98.04	105.88
36. Coke	1.10×10^{5}	25.05	12.53	34.45	40.71	28.19	194.17	9.40	25.05	18.79
37. Gasoline	1.05×10^{5}	53.43	48.45	35.32	38.04	33.51	38.94	18.11	40.30	41.20
38. Kerosene	1.10×10^{5}	16.13	17.55	21.82	23.24	34.63	46.96	77.80	66.89	73.05
39. Diesel	1.10×10^{5}	43.22	3.76	71.87	61.54	86.43	88.78	139.52	135.76	131.06
40. Fuel oil	1.10×10^{5}	15.66	0.00	2.76	7.37	7.37	12.43	13.82	16.12	12.90
41. Liquefied petroleum gas	1.11×10^{5}	2.79	2.79	4.46	3.35	4.46	12.27	3.90	2.23	1.67
42. Goods in exports	1.14×10^{13}	925.68	1198.48	1364.47	1438.00	2344.87	4326.76	6549.76	6320.05	6798.05
43. Services in exports	1.14×10^{13}	103.73	211.24	243.06	394.43	584.39	1076.59	1551.34	2206.67	2871.38
Waste										
44. Liquid waste	9.87×10^{6}	12.96	13.20	15.20	16.50	17.30	18.50	17.80	20.61	21.20
45. Solid Waste	1.80×10^{6}	0.07	0.07	0.07	0.06	0.08	0.08	0.07	0.08	0.07

Table 4 presents the indices for evaluating the urban metabolic status of Beijing. From 1996 to 2012, "F" of Beijing increased about 7.64 times, during which "S_2" decreased from 21.59% to 1.43%. In 2012, imported resources emergy account for 98.41% of flux (S_3), which shows that the socioeconomic development of Beijing was highly dependent on imported resources. "S_1" fluctuated every year, and the value reached 10.01% in 2012. From this, we can infer that the green development mode has achieved initial results, but that there is still an opportunity to reduce the consumption of non-renewable resources.

"I" increased 4.26 times, which shows that, on the one hand, the living standard of urban residents has improved; while on the other hand, it reveals an unreasonable production and living structure, with improved social and economic conditions still based on a large amount of resource consumption.

"E" was on the rise from 1996 to 2012. In 2012, the value was 9.99×10^{-14}: higher than that of Shanghai in 2010 (3.97×10^{-14}), Shenzhen in 2010 (4.78×10^{-14}), and Suzhou in 2010 (4.69×10^{-14}), but lower than Guangzhou in 2010 (1.13×10^{-13}) [59]. This indicates that the utilization rate of resources of Beijing is higher than that of most fast-growing cities in China.

"W" decreased from 1996 to 2012, which reflects that environmental stress has decreased. In the meantime, the waste of resources was reduced year by year, and the energy utilization ratio increased gradually.

Table 4. Emergy indices for evaluating Beijing urban metabolism from 1996 to 2012.

Index	**Value**								
	1996	**1998**	**2000**	**2002**	**2004**	**2006**	**2008**	**2010**	**2012**
F [a]	3.28	3.34	4.51	4.93	7.14	10.74	16.82	20.24	28.36
S1	4.66%	4.59%	3.49%	3.22%	3.32%	2.83%	4.09%	4.47%	10.01%
S2	21.59%	21.91%	15.68%	15.16%	12.31%	7.88%	5.29%	3.22%	1.43%
S3	77.35%	77.04%	83.75%	84.34%	87.27%	91.89%	94.48%	96.63%	98.41%
I [b]	2.61	2.68	3.32	3.46	4.79	6.79	9.92	10.32	13.71
E [c]	6.56	8.61	8.47	10.58	10.20	9.55	9.51	10.30	9.99
W	0.40%	0.40%	0.34%	0.34%	0.24%	0.17%	0.11%	0.10%	0.07%

[a] Unit = 10^{23} seJ, [b] Unit = 10^{16} seJ/person, [c] Unit = 10^{-14} US$/seJ.

3.2. Analysis of Land Use Change

The total urban land area of Beijing is 16,410.54 km^2. The trends in change of three kinds of urban land in Beijing are presented in Figure 2. The area of farmland decreased each year from 1996, while the percentage of built-up land went from 16.51% in 1996 to 21.63% in 2012, and the percentage of unused land decreased to 12% in 2012. With development of urbanization, there will be a larger population crowded into the city, more built-up land will be needed, hence farm land will continue to be reduced, and more unused land will be developed by advanced science and technology.

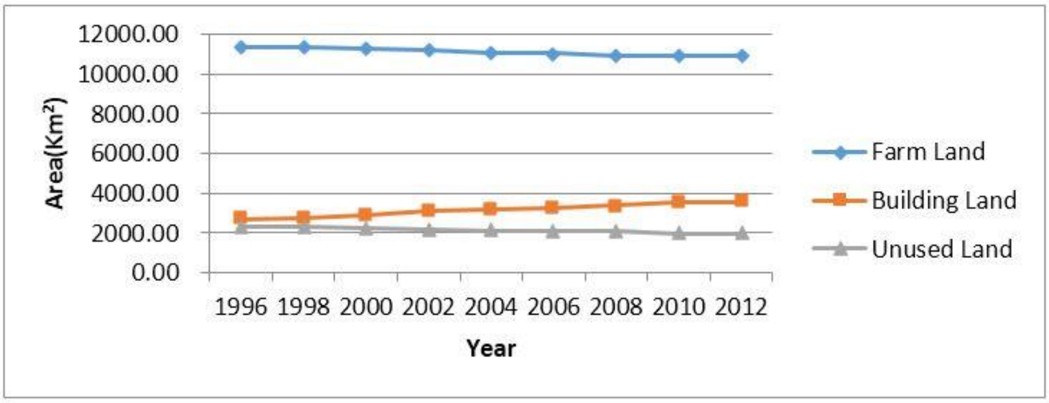


Figure 2. The change of different kinds of land area of Beijing from 1996 to 2012.

3.3. Emergy-Based Indices for Land Use Analysis

3.3.1. Emergy-Based Evaluation of the Whole Urban Area

Table 5 presents the emergy-based indices for evaluating land use of Beijing from 1996 to 2012. Because the area is constant, the growth of "D" is the same as that of "F". EYR indicates fluctuating decline, which reveals that rapid development was highly dependent on plenty of emergy input. ELR increased remarkably. We can infer that this was the result of a large amount of external-resource feedback into the urban land system, which lead to a significant increase in land load emergy. Although resource exploitation and occupation slowly declined, it was not sufficient to ease land-bearing pressure. ESI of Beijing also decreased sharply during the 16 years. The range of ESI values fell remarkably from 1998 to 2000, while the trend of decline was stable after 2010. M. T. Brown and S. Ulgiati [60] provided a quantitative criterion empirically for evaluating the land emergy sustainable indices (ESI). An ESI < 1 indicates a consumer-economic urban system, ESI > 10 indicates underdeveloped economies, and the economy has huge potential for development when $1 \leq ESI \leq 10$. The ESI value of the Beijing urban system is low (only 5.89×10^{-4} in 2012), and the imported emergy and total emergy are high. This means that Beijing is a typical consumer-economic urban system.

Table 5. Emergy-based indices for evaluating urban land use in Beijing from 1996 to 2012.

Indices	Value								
	1996	1998	2000	2002	2004	2006	2008	2010	2012
D	2.00×10^{13}	2.03×10^{13}	2.75×10^{13}	3.00×10^{13}	4.35×10^{13}	6.55×10^{13}	1.03×10^{14}	1.23×10^{14}	1.73×10^{14}
EYR	0.51	0.60	0.51	0.53	0.52	0.59	0.53	0.46	0.37
ELR	93.84	93.81	175.25	197.42	235.24	435.16	441.90	663.98	627.34
ESI	5.45×10^{-3}	6.37×10^{-3}	2.92×10^{-3}	2.70×10^{-3}	2.23×10^{-3}	1.36×10^{-3}	1.20×10^{-3}	6.96×10^{-4}	5.89×10^{-4}

Although the Beijing government adopted a series of measures that reinforced protection and construction of the ecological environment, lack of cooperation with other surrounding cities is a barrier to industrial relocation, and lower public awareness and inadequacy of action had negative effect on economic transition, thus the conflict between environmental protection and socioeconomic development still exists [61]. For this period, the production mode of relying on external resources could not be changed, and the problem of land use sustainability could not be solved effectively.

3.3.2. Emergy-Based Evaluation of Farm Land

We divided the material and energy of farmland into renewable resources, nonrenewable resources, industrial auxiliary resources (including chemical fertilizer, plastic, pesticides, rural electricity, farm machinery, and farm diesel fuel) and labor. As shown in Table 6, we calculated the emergy-based indices for evaluating farmland use in Beijing. From 1996 to 2012, the industrial energy input of farmland indicated fluctuating decline, and the industrial energy input per unit area declined as well, with the decrease of farmland area. "D" of farmland indicates modest change from 1996 to 2006, while it increased remarkably after 2006. The value was 0.90 times more in 2012 than in 1996. The EYR of farmland presented a trend of increase after initial decreases. At its peak, the value was 11.56 in 2002, and declined almost 1.70 times by 2012. This reveals that the emergy yield ratio declined with decreasing industrial energy input, and that farmland output was highly dependent on fossil energy input. The ELR of farmland increased slightly from 1996 to 2012, but compared to that of Shanxi in 2004 (6.55) [62], Jiangxi in 2009 (6.94) [63], Gansu in 2004 (6.08) [64], Hebei in 2005 (5.72) [65], and Hunan in 2008 (7.25) [66], there is still a certain space for increasing ELR. The value of ESI indicates fluctuating decline. In 2012, the ESI value of farmland was 1.37 (1 < ESI < 10), indicating that farmland still had potential for utilization, and this is still far more than the ESI value of Fujian in 2010 (0.42) [67], Xi'an in 2006 (0.78) [68], and Xuzhou in 2006 (0.07) [69]. Beijing has developed urban modern agriculture for more than 10 years, the agriculture management model changed from limited function to multifunction earlier [70], and the more reasonable land use pattern resulted in a more sustainable development of farmland than in other provinces and cities.

Table 6. Emergy-based indices for evaluating farmland use in Beijing from 1996 to 2012.

Index	Value								
	1996	**1998**	**2000**	**2002**	**2004**	**2006**	**2008**	**2010**	**2012**
Industrial energy input (seJ)	6.49×10^{20}	5.32×10^{20}	5.65×10^{20}	4.99×10^{20}	5.15×10^{20}	4.76×10^{20}	3.89×10^{20}	3.60×10^{20}	3.57×10^{20}
Industrial energy input per unit area (seJ/m^2)	5.71×10^{10}	4.69×10^{10}	5.01×10^{10}	4.46×10^{10}	4.65×10^{10}	4.31×10^{10}	3.55×10^{10}	3.29×10^{10}	3.28×10^{10}
D	4.24×10^{11}	3.74×10^{11}	3.75×10^{11}	3.92×10^{11}	4.34×10^{11}	4.18×10^{11}	6.15×10^{11}	6.38×10^{11}	8.06×10^{11}
EYR	7.79	9.42	10.17	11.56	10.48	9.22	6.49	6.18	4.75
ELR	1.40	1.07	2.02	2.17	2.06	2.63	2.76	3.32	3.46
ESI	5.58	8.81	5.03	5.32	5.07	3.50	2.36	1.86	1.37

3.3.3. Emergy-Based Evaluation of Built-up Land

Table 7 shows the emergy consumption of energy and cement, their unit consumption, and other emergy-based indices. We selected cement consumption to represent the building material consumption, thus analyzing the change of urban demand for resources with the continued expansion of built-up land.

Table 7. Emergy-based indices for evaluating built-up land use in Beijing from 1996 to 2012.

Index	Value								
	1996	1998	2000	2002	2004	2006	2008	2010	2012
Energy Emergy Consumption (seJ)	9.90×10^{22}	1.13×10^{23}	1.26×10^{23}	1.38×10^{23}	1.59×10^{23}	1.74×10^{23}	2.14×10^{23}	2.43×10^{23}	2.57×10^{23}
Unit Energy Consumption (seJ/m^2)	3.65×10^{13}	4.09×10^{13}	4.32×10^{13}	4.48×10^{13}	4.95×10^{13}	5.31×10^{13}	6.34×10^{13}	6.92×10^{13}	7.23×10^{13}
Cement Emergy Consumption (seJ)	1.01×10^{22}	1.18×10^{22}	1.39×10^{22}	1.49×10^{22}	2.04×10^{22}	2.14×10^{22}	3.73×10^{22}	1.76×10^{22}	1.55×10^{22}
Unit Cement Consumption (seJ/m^2)	3.72×10^{12}	4.26×10^{12}	4.75×10^{12}	4.81×10^{12}	6.37×10^{12}	6.53×10^{12}	1.11×10^{13}	5.02×10^{12}	4.37×10^{12}
D	1.13×10^{14}	1.10×10^{14}	1.46×10^{14}	1.52×10^{14}	2.18×10^{14}	3.22×10^{14}	4.92×10^{14}	5.70×10^{14}	7.92×10^{14}
EYR	0.74	0.89	0.73	0.75	0.69	0.73	0.64	0.57	0.45
ELR	638.53	609.53	1175.21	1227.97	1536.00	2800.02	3000.70	3862.92	4379.32
ESI	1.16×10^{-3}	1.46×10^{-3}	6.24×10^{-4}	6.08×10^{-4}	4.50×10^{-4}	2.60×10^{-4}	2.13×10^{-4}	1.47×10^{-4}	1.03×10^{-4}

From 1996 to 2012, energy emergy consumption, and its unit consumption in Beijing, increased constantly. More building materials were used because of increased urban construction. Cement emergy consumption shows a slowly increasing trend from 1996 to 2006, while it increased substantially in the period 2006–2008, as a result of Olympic venue construction. After 2008, the consumption gradually dropped to 1.55×10^{22} seJ. The unit cement consumption shared the same changing trend as cement emergy consumption.

"D" of built-up land increased constantly over the 16-year study period (1996 to 2002), though the growth rate was slower after 2002. The value was 7.01 times higher in 2012 (as much as it was in 1996), while the energy and cement emergy consumption increased 2.50 times. This shows that except for the consumption of natural resources, the rapid development of tertiary industries has greatly affected the urban metabolism.

The EYR of built-up land indicates fluctuating decline from 1996 to 2012, which reveals that with the expansion of built-up land, urban construction cost became higher and higher, and the return was not in accord with the degree of effort, in the process of urban construction. From 1996 to 2012, the ELR value increased and the ESI value decreased remarkably. The high-intensity utilization of built-up land, because of rapid population growth and over-agglomeration in the city center, puts it under too much pressure [71].

3.4. Correlation Analysis of Urban Metabolism and Land Use Changes

To evaluate the impact of land-use type on urban metabolism, we calculated the correlation coefficient of the increments of farmland, built-up land, and total land emergy-based indices, As shown in Table 8, we can figure that the emergy use of built-up land had a more significant effect on urban total emergy change, than the emergy use of farmland did, and that its metabolic density affected the urban metabolic density strikingly as well. There was a weak correlation between the emergy yield ratios of farmland metabolism and urban metabolism. The coefficient displayed a substantial correlation with the environmental load ratio of building-land metabolism and urban metabolism, as well as with the emergy sustainable indices. The five correlation coefficients show that Beijing urban development largely depended upon production activities on built-up land, while the role of agricultural production in urban development was relatively insignificant.

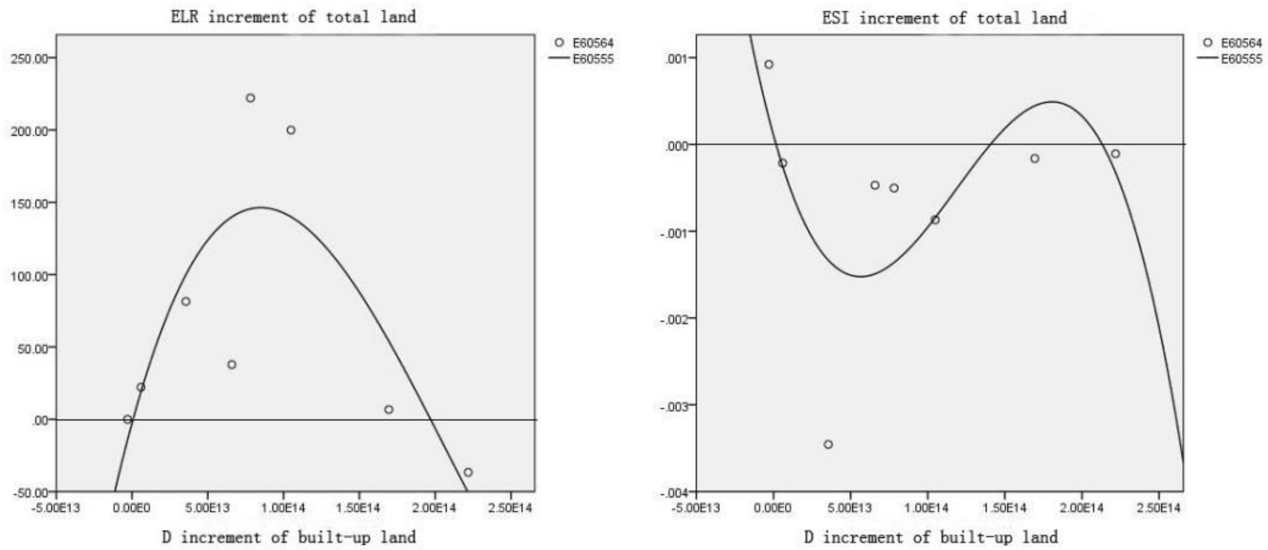
Table 8. Correlation coefficients of 2-year increments of several emergy-based indices.

Land Use	Correlation Coefficients				
Type	**U**	**D**	**EYR**	**ELR**	**ESI**
Farmland	0.8586	0.8566	0.3992	0.6321	0.8885
Build-up land	0.9999	0.9958	0.9485	0.8151	0.9933

From the aspect of land-use intensity, we tried regression fitting of the D increment of built-up land and ELR increment (ESI increment) of total land with different models in the software SPSS 22.0. According to spatial correlations between the dependent variable and the independent variables, we found that the most fitting formulation of the spatial regression model was Equation 2 (between D increment of built-up land and ELR increment of total land), and Equation 3 (between D increment of built-up land and ESI increment of total land). The change curves are shown in Figure 3. The results show that the ELR increment of total land appears to indicate negative growth when D increment is less than 6.74×10^{11} or greater than 1.97×10^{14}. When D increment is 8.49×10^{13}, the ELR increment reaches the maximum. ESI values increase when D value decreases or the increment is between 1.46×10^{14} and 2.10×10^{14}. ESI reaches maximum when D increment is 1.81×10^{14}. We found that when D increment is between 1.46×10^{14} and 1.97×10^{14}, the ELR value decreases while ESI value increases, *i.e.*, the development has a positive effect on the urban environment.

$$y = 4.575 \times 10^{-41} x^3 - 2.843 \times 10^{-26} x^2 + 3.837 \times 10^{-12} x - 2.573 \quad (2)$$

$$y = -2.107 \times 10^{-45} x^3 + 7.490 \times 10^{-31} x^2 - 6.441 \times 10^{-17} x \quad (3)$$



(**a**) (**b**)

Figure 3. (**a**) Trend of metabolic density (D) increment-environmental load ratio (ELR) increment and (**b**) Trend of D increment-ESI increment in the Beijing urban system.

4. Conclusions

In this paper, we calculated some emergy-based indices by which to evaluate the mechanisms and characteristics of Beijing socioeconomic development. Along with land utilization, we used calculated emergy-based indices of land use change, to analyze the interactions between land use and urban metabolism, based on correlation analysis and regression analysis. We reached the following primary conclusions:

(1) Waste emission of Beijing was reduced in recent years, and the utilization rate of resources is higher than in most of the fast-growing cities of China. However, Beijing is a typical consumer-economic urban system, which relies on the consumption of materials and energy. The production activities on built-up land depended on exploitation of local non-renewable resources and on external resource input, and the emergy sustainable indices decreased to almost zero. While there is a continued slowdown in emergy utilization and sustainability of farmland, but the farmland still has more utilization potential than in most provinces and cities of China. According to the correlation analysis, urban development in Beijing relies on production activities on built-up land, which is subjected to great environmental pressure during extraction of material resources. However, while the value of metabolic density of built-up land is between 1.46×10^{14} and 1.97×10^{14}, there is a positive effect on urban environment, which provides a reliable reference for intensive and compact use of urban land.

(2) The research on urban metabolism and land use based on emergy analysis magnifies every link of land use and metabolism, thus revealing the details of urban development. This makes it possible to conduct specific research on different problems, and to bridge the gap in correlation research, between urban metabolism and land use. The measuring units of materials, energy, and capital are always different, thus it is difficult to compare or combine them in one system, while analysis of the dynamics of emergy indices of different kinds of land, can solve the problems of conflicting measurement units, and avoid the disadvantages of subjective assignment. Each kind of industrial and agricultural product produced by different modes and at different levels has different resource input and output, so its solar transformity is different also, but we used a single transformity value for some resources, thus leading to the inaccuracy of material, energy, and capital emergy in the emergy-analysis method. However, the error is acceptable in the research of urban systems [72].

(3) To realize sustainable development of urban social economy and land use, we suggest that it is necessary to reduce the input of external feedback emergy, reuse materials, recycle products, and control wastes [73], to commit to development of a circular economy. Regarding land administration, the concept of urban land use should be changed to traffic accessible, land-use efficient, and ecological "Smart Growth" [74], to reduce energy consumption and environmental cost. Moreover, developing the potential of farmland appropriately, and popularizing metropolitan modern circulating agriculture of plant-production/animal-transformation/microbial-loop/process model, *etc.* [75] is necessary to reduce the urban load pressure.

(4) To achieve efficient use of land resources and sustainable urban development, we need further research. First, we need more study about the mechanism of effects between land use and urban metabolism. If we find the key point of land use change, and material, energy, and capital flow

change, we might then construct a better land use pattern that is less consumption oriented, has high metabolic efficiency, and is more eco-friendly. Second, we need to apply methods and models to more cases, combined with spatial information sciences, and to compare the research results of these different cases on temporal and spatial scales. Then we might give reliable suggestions on land use and urban sustainable development. Third, we need to explore more methods by which to analyze land use and urban metabolism on different scales, and to evaluate the effect of methodological pluralism. In this way, we might provide new ideas for land administration and urban planning, and also provide a basis for solving urban ecological problems.

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Author Contributions

Xinqi Zheng and Qing Huang designed this study; Qing Huang retrieved and analyzed the data, and wrote the paper; Xinqi Zheng and Yecui Hu revised the paper. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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