Entropy **2011**, *13*, 720-743; doi:10.3390/e13030720

OPEN ACCESS

entropy

ISSN 1099-4300

www.mdpi.com/journal/entropy

Article

Analysis of Resource and Emission Impacts: An Emergy-Based Multiple Spatial Scale Framework for Urban Ecological and Economic Evaluation

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Received: 3 December 2010; in revised form: 17 January 2011 / Accepted: 1 March 2011 / Published: 23 March 2011

Abstract: The development of the complex and multi-dimensional urban socio-economic system creates impacts on natural capital and human capital, which range from a local to a global scale. An emergy-based multiple spatial scale analysis framework and a rigorous accounting method that can quantify the values of human-made and natural capital losses were proposed in this study. With the intent of comparing the trajectory of Beijing over time, the characteristics of the interface between different scales are considered to explain the resource trade and the impacts of emissions. In addition, our improved determination of emergy analysis and acceptable management options that are in agreement with Beijing's overall sustainability strategy were examined. The results showed that Beijing's economy was closely correlated with the consumption of nonrenewable resources and exerted rising pressure on the environment. Of the total emergy use by the economic system, the imported nonrenewable resources from other provinces contribute the most, and the multi-scale environmental impacts of waterborne and airborne pollution continued to increase from 1999 to 2006. Given the inputs structure, Beijing was chiefly making greater profits by shifting resources from other provinces in China and transferring the emissions outside. The results of our study should enable urban policy planners to better understand the multi-scale policy planning and development design of an urban ecological economic system.

Keywords: urban system; emergy evaluation; multiple spatial scale

1. Introduction

Due to the complex and multi-dimensional urban socio-economic system, the knowledge of the organizational structure, urban energy and material inward-outward flows [1], capturing the trade-offs between natural, economic and social capital [2] is a major step towards the design of sustainable development schemes. Meanwhile, as governments are increasingly concerned about international negotiations, cooperation, and conflicts on climate change issues, the traditional environmental problems in cities such as waste water removal, sanitation, water supply, indoor and exterior air pollution, *etc.* have been proven to have a cross-regional impact [3]. Analysis of individual urban processes is not enough for understanding the inherent functional principles and evaluating their environmental performance since such a narrow view may indistinguishably consider international and regional trading [4] or simply shift the environmental impacts to the other parts of local economic activities life cycle [5]. Challenges for urban development from a sustainable perspective have been divided into two categories: (1) modes of resource supply; (2) the activity boundary that outlines the emissions emitting operations for which a city is responsible and that must be accounted for in the city's mass/energy balance. As a consequence, urban socio-economic performance metrics must be capable of linking local scales and extend further to the economy and ecosystems scales [6]. With the international trading network taken into account, fruitful studies focusing on specific countries have been presented [7–13]. There is an urgent need to develop a quantitative methodology that can evaluate both the resource supply and the adverse environmental effects of urban socio-economic systems at different scales and take into account how they affect the urban system's dynamics and sustainability.

Methods relying on input-side information have also been developed, usually based on mass [14], energy [15], exergy [16], emergy [17–20] and ecological cumulative exergy consumption [21]. Emergy synthesis is a method of environmental accounting derived from energy system theory that uses the energy (in units of the same kind) required to produce a good or service as a nonmonetary measure of the value or worth of components or processes within ecosystems and the economy [22]. The Emergy synthesis method transcends systems' analysis boundaries, considers resource inputs and environmental contributions, and constructs the basic emergy-based index system [23]. Until now, a large number of systems have been evaluated by means of the emergy method on regional and national scales [19,20,24–31]. Most of these studies, however, did not focus on the multiscale analysis of resource supply and emissions impact, although important steps ahead have been taken in that direction. Chen and Shonnard [32] presented a hierarchical approach for environmentally conscious chemical process design based on the Analytic Hierarchy method. Brown and Ulgiati [33] applied the emergy method to suggest a system view of ecosystem integrity and also to assess the emergy investment needed to restore ecosystem health. Bakshi and his colleagues proposed a multiscale statistical framework for life cycle inventory analysis in some case studies of the U.S. economy and the CGAM cogeneration system [5,34–36]. Four kinds of spatial hierarchy structures were defined,

including economy, life cycle, equipment and hybrid scale, yet the majority of these works have just developed a conceptual framework rather than specify a detailed list of the different emission categories, especially the emission impacts on different scales. As a smaller control unit, the city nests in a nation's economic system, which is different from the doubly-nested world economic system. A city's expanding resources consumption requires its neighbors to expend (considering the factor of state socioeconomic regulation) and purchase from abroad; meanwhile, a city should be held accountable for its "external" emissions. Here, emergy algebra was used to quantify the values of human-made and natural capital losses which were considered as indirect inputs of ecological services for airborne and waterborne pollutants dilution and damage repair or replacement to "internalize" the "externalities" with emphasis on a joint application of the emergy synthesis and LCA methods. The results obtained are potentially useful in understanding the supply networks of a city belonging to different hierarchical levels of the economy and would enable decision-makers to target emission policy measures by purchasing third-party offsets.

This paper proposes an emergy-based multiple spatial scale analysis framework and a rigorous accounting method that can quantify the values of human-made and natural capital losses. With the intent of comparing the trajectory of Beijing, the characteristics of the interface between different scales are considered for explaining the resource trade and the impacts of emissions. In addition, we examine our improved determination of emergy analysis and acceptable management options that are in agreement with Beijing's overall sustainability strategy.

As a follow-up work of our earlier effort to make an assessment evaluating the environment and economic development in Beijing's socio-economic system on a common base [29,30,37,38], this work serves as a further attempt to assess both the energy resource consumption and the adverse environmental effects in a unitary manner from a cross-regional perspective based on emergy analysis.

2. Methods

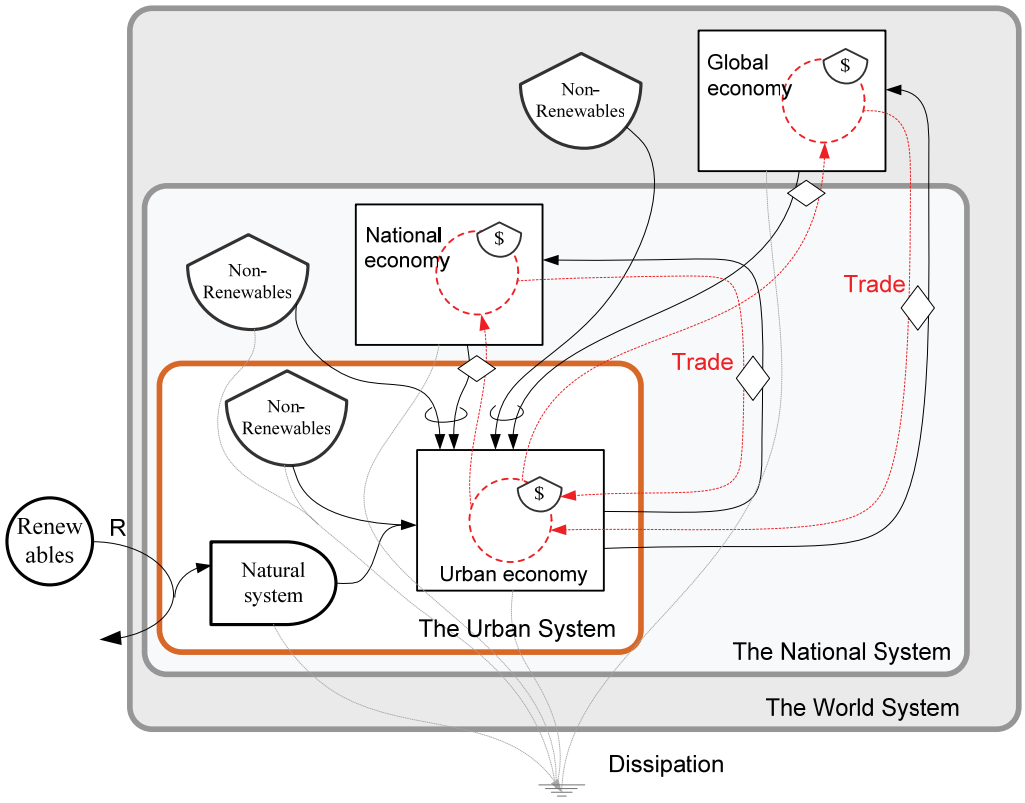
2.1. Emergy-Based Multiple Spatial Scale Analysis Model

Emergy is formally defined as all the available energy of one kind previously used up directly and indirectly to make a product or service [39,40]. As a thermodynamic-based environmental accounting approach, the emergy synthesis converts all materials, energy sources, human labor and services required directly and indirectly into emergy unit that are summed up to yield the total emergy [22]. Emergy analyses are carried out using transformities, specific emergies and other factors that are determined according to a particular planetary baseline [22,41], which is decided by the solar equivalences of the three primary energy inputs to the biogeosphere, *i.e.*, solar radiation, residual and deep heat of the Earth, and the gravitational attraction of the sun and moon. In this study, transformities were converted from global emergy baseline of 9.44×10^{24} to 15.83×10^{24} seJ/yr recommended by Brown and Ulgiati [41].

A typical diagram describing an urban system is shown in Figure 1, where the standard energy system symbols are used [22]. At the planetary level of organization, there are no substantial exchanges with the larger system, except for solar and gravitational energy entering the system from external sources. Within the large box, they indicate the spatial boundaries of the urban system, renewable emergy (R), *i.e.*, the rain, wind, tides, waves, *etc.*, Nature also does work that indirectly

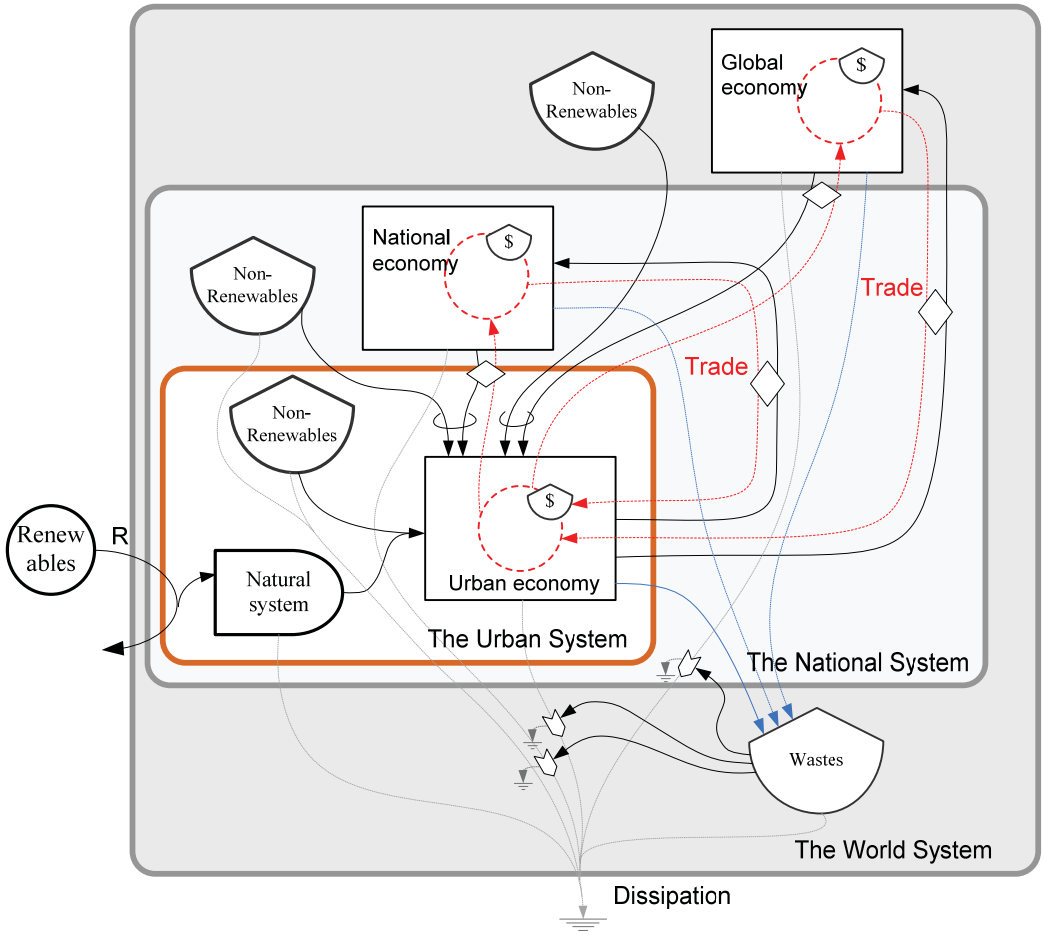
supports the activities of the world socioeconomic system (e.g., the photosynthesis of natural ecosystems that fixes carbon and replenishes oxygen in the atmosphere, which is necessary for all life, the movement of clean air that replaces contaminated air over cities and water flows that supply the capacity to dilute municipal wastes). The emergy provided by fuels and electricity is modeled on a separate pathway that acts on the material products arranging and ordering them. Humans extract and process the slowly renewed material products of natural work in the environmental system, *i.e.*, fossil fuels and minerals. These inflows are considered to be nonrenewable because they are being used by socioeconomic system at a rate that is much greater than their natural renewal rate. Human work is also used to carry out economic production using these raw materials and to carry out the other processes and functions of society.

Figure 1. The urban socio-economic system position and role in the national and world system, described in terms of net emergy flows and trade (without considering transport of pollutants).



The multiple spatial scales between the environment and human socioeconomic systems can most easily be understood by modeling the world system as a whole (see Figures 1 and 2). Emergy and associated systems language also provides a tool for illustrating energy and material flows between regions, as well as controlling (feedback) mechanisms. In other words, it becomes possible to visualize the flows and interactions referred to above, and simplify them through aggregation, thereby enabling the human mind to conceptualize small and large parts simultaneously, and hence see the bigger picture more clearly. By drawing on the results in this thesis, and the example above, Figure 1 therefore illustrates the urban system's position and role in both the national and world system, depicted in emergy systems language.

Figure 2. The urban socio-economic system position and role in the national and world system, described in terms of net emergy flows and trade (considering transport of pollutants).



However, even if resources or pollutions embodied in trade are fully understood and international responsibilities are reallocated on a consumption basis, it is far from enough to promote global cooperation to combat economic loss and ecological impacts. It would be great progress, though, not to mention that net pollution importers may not accept consumption-based methods. Figure 2 represents the waste released and its interaction with the urban system itself. Air and water emissions and solid waste are controlled based on additional input of fuels, goods and labor force. Thus, simply trying to seek a single global solution that is implemented by national governmental units because of global impacts is far from satisfactory. The essential role of smaller-scale effects must be recognized. In this sense, a polycentric approach might be an alternative for the problem, which means actions at various levels with active oversight of urban, regional, and national boundaries.

As we live in a highly globalized world, economies of scale and comparative advantages exist in certain areas, rendering trade and commerce highly valuable and emissions "ownership" more complex. The processes described in Figures 2 are similar in many ways, but have one major difference; on a more aggregate scale, not only is control fed back, but waste is also generated by the world system. Put together, this means that the city draws on local environmental and human resources, together with non-renewable energies from other peripheries, hence facilitating the process of

accumulation in the core, only to risk exhausting the local, national and global resource base, and building up stored waste. With this current voluntary set-up and focus solely on emissions produced in each country, and in the globalized world in which we live, a perverse incentive exists for industrialized countries to transfer high emitting activities to the developing world.

2.2. Emergy Algebra

Emergy algebra comprises two parts: (1) resources and energy inputs and (2) emission impacts. The emergy embodied into an imported product is made up of two parts, one is from geobiosphere work and the other one is from services needed for its production during previous manufacturing steps [23]. Here, a monetary measure is used to account the indirect labor embodied in the production and delivery of imported goods.

In the waste side, Ulgiati *et al.* [42] focused on the emergy resources required in order to prevent or fix reversible damages. Moreover, they pointed out that: (1) additional emergy resources are needed to replace the lost assets or units, when irreversible damages occur, and that (2) when replacement is not possible, at least a conservative estimate of the natural or human capital loss should be attempted, based on the resources previously invested for its generation, in order to ascertain the true cost of a process product. Following Ulgiati *et al.* [42] and Ulgiati and Brown [43], additional emergy cost terms should be included in order to account for: (a) dilution and abatement of emissions by natural processes, (b) abatement, uptake and recycle of emissions by means of technological devices, (c) repair of damages to human-made assets by means of maintenance activities, (d) reversible and irreversible damages to natural capital (e.g., loss of biodiversity), and finally (e) reversible and irreversible damages to human health. As a consequence, the total emergy cost U (here, U = used) can be calculated as:

$$U = R + N + F + F_1 + \ldots + F_n \quad (1)$$

where R and N are respectively the locally renewable and nonrenewable emergy resources, F is the emergy of imported goods and commodities (including their associated services) and where the F_i terms include the environmental or human-driven emergy investments (here, F = feedback) needed to prevent or fix the damages occurred and charged to the process:

$F_1 = \Sigma_j F_{1,j}$ = the sum of all j-th input flows to prevent or fix damage 1;

…

$F_n = \Sigma_k F_{n,k}$ = the sum of all k-th input flows to prevent or fix damage n.

In this study, a preliminary damage assessment of losses is performed according to the framework of the Eco-Indicator 99 assessment method [44] as well as the authors' own preliminary work [30,31]. Such a method, like all end-point life cycle impact assessment methods, suffers from very large uncertainties intrinsically embodied in its procedure for assessment of final impacts. Damages to natural capital are expressed as the Potentially Disappeared Fraction (PDF) of species in the affected ecosystem, while damages to human health are expressed as Disability Adjusted Life Years (DALY), according to references [44–46]. The impact of emissions on human health can be viewed as an additional indirect demand for resource investments. Human resources (considering all their complexity: life quality, education, know-how, culture, social values and structures, hierarchical roles,

etc.) can be considered as a local slowly renewable storage that is irreversibly lost due to the polluting production and use processes. The emergy loss can be calculated as:

$$L_{w,1}^{*} = \sum m_i^{*} \times \mathrm{DALY}_i \times \tau_H \quad (2)$$

where, $L_{w,1}^{*}$ is the emergy loss in support of the human resource affected, i refers to the i-th pollutant, m^{*} is the mass of chemicals released, DALY is its E.I. 99 impact factor and τ_H is the unit emergy allocated to the human resource per year, calculated as τ_H = total annual emergy/population.

The effect of Potentially Disappeared Fraction of Species (PDF) can be quantified as the emergy of the loss of local ecological resources, under the same rationale discussed above for the human resource:

$$L_{w,2}^{*} = \sum m_i^{*} \times \mathrm{PDF}(\%)_i \times E_{Bio} \quad (3)$$

where, $L_{w,2}^{*}$ is the emergy equivalent of the impact of a given emission on urban natural resource, PDF(%) is the fraction potentially affected, measured as PDF × m^2 × yr × kg^{-1}.

Finally, damage associated with solid waste generation can be measured by land occupation for landfill and disposal. This may be converted to emergy via the emergy/area ratio (upper bound, average emergy density of economic activities) or even via the emergy intensity of soil formation (lower bound, average environmental intensity). Thus the related emergy loss ($L_{w,3}$) can be obtained using the total occupied land area multiplied by the economic or environmental emergy intensity of such an area (choice depends on the area of the investigated system).

2.3. Case Study

Beijing (N115°25–117°30′, E39°26′–41°03′) lies at the eastern edge of the Eurasian continent and belongs to the Bohai sea rim economic circle, with small plains in the south and mountains in the west and north, covering an area of 16,807.8 km^2. Characterized by its long history and central political and cultural position, Beijing is amongst the most developed cities in China with a fully integrated industrial structure, including electronics, machinery, chemicals, light industry, textile and automobile manufacturing. Like other metropolis in developing countries, Beijing faces the dilemma of urban economic development *versus* social and ecological problems comprising the large floating population, high-yield agricultural land loss, resource shortages, high levels of pollution, ecological deterioration, and increasing risks of disaster. The evolution of the Beijing urban system can be treated as a history of resource consumption and accumulation, which has, in turn, brought about the changes in the urban structure and organization. As mentioned above, most of these intensive resources consumed in Beijing are purchased from outside with the exception of a small proportion of the fuels and minerals. Also, all the flows of resources are accompanied with human services and money flows.

The reason for choosing Beijing as the primary study site for this research is that Beijing is a major node linking China and the world and the nation and its provinces. The strong nationwide support for the 2008 Olympic Games in Beijing—hosted at the expense of investments elsewhere in the country—offers a typical example of the Chinese desire for global recognition. The successful hosting of this globally significant event is seen as firmly demonstrating China's winning a central position on the world stage. This interpretation is possible because Beijing as the capital city represents China to the

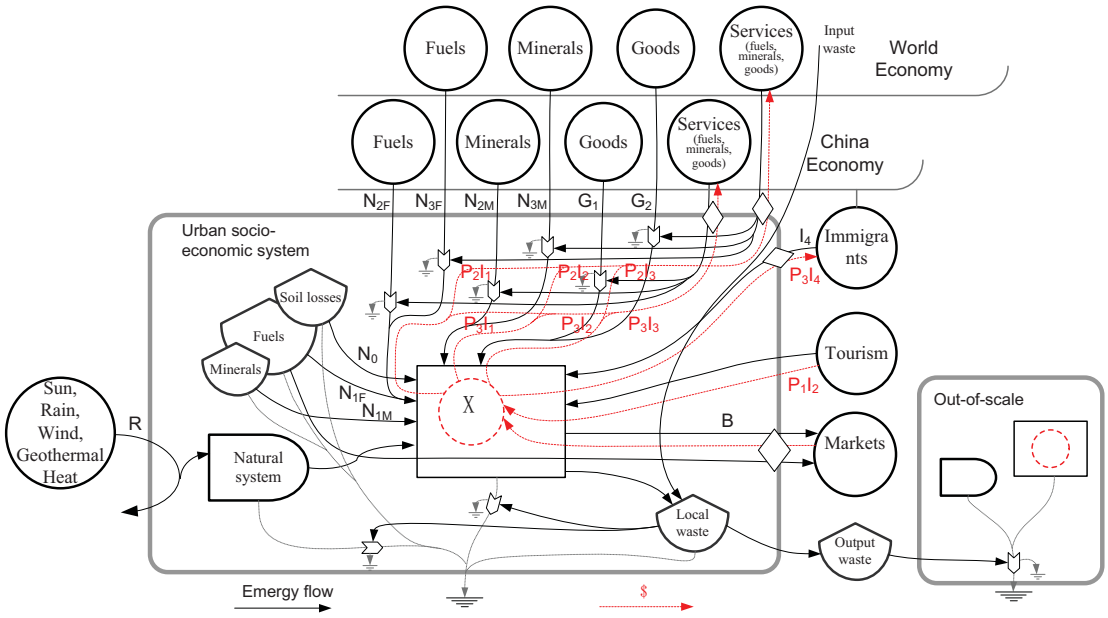
outside world. This paper focuses on how Beijing—in terms of both its physical reality and how it is imagined—mediates the interesting dynamics among various local, national, and global processes.

3. Results

3.1. Main Emergy Flows in Beijing

Figure 3 shows the inputs and internal structures of Beijing that were quantified in this study. We evaluated the emergy inputs supporting economic activities of urban system and compared the emergy inflows to measures of economic activity in Beijing. The following major classes of emergy inputs supporting Beijing from 1999 to 2006 were documented: (1) renewable energy sources, (2) soil erosion, (3) energy consumption, (4) minerals consumed, (5) imported goods other than fuels and minerals, (6) imported services in goods, fuels and minerals, (7) imported services, and (8) immigrants.

Figure 3. Summary flow diagram for the main emergy flows in Beijing.



3.2. The Determination of Pollutants

Our study deals with the emissions harmful to human health and the ecosystem listed in Table 1. Air emission discharges from both urban production and use include SO_2, dust, NO_x and CH_4 (respiratory disorders), CO_2, N_2O and CH_4 (climate change). Eight waterborne pollutants (mercury, cadmium, hexavalent chromium, lead, arsenic, volatile phenol, cyanide, oil) were selected as indicated. The loss fractions of human health and ecosystem quality (DALY/kg of emission, PDF × m^2 × yr) are collected in the reference [44]. The emission data related to SO_2, dust, and NO_x were collected from governmental publications, such as the Beijing Statistical Yearbook and the Chinese Environmental Statistical Yearbook [47,48]. Data about CO_2, N_2O and CH_4 are calculated as greenhouse gases released at local and global scales, based on direct and indirect energy consumption, that in turn are evaluated according to the Embodied Energy Analysis method [49,50]. The embodied energy of

materials and energy flows is calculated by multiplying local inputs by appropriate Oil Equivalent Factors.

Table 1. Lists of emissions and environmental impacts.

Type of Pollution	Pollutant	Damage Category Human Health	DALY/kg of Emission	Damage Category Ecosystem Quality	PDF × m^2 × yr
Airborne pollution	CO_2	Climate change	2.10×10^{-7}		
	NO_x	Respiratory disorders	8.87×10^{-5}	Acidification	5.71
	SO_2	Respiratory disorders	5.46×10^{-5}	Acidification	1.04
	Dust	Respiratory disorders	3.75×10^{-4}		
	N_2O	Climate change	6.90×10^{-5}		
	CH_4	Respiratory disorders	1.28×10^{-8}		
	CH_4	Climate change	4.40×10^{-6}		
Waterborne pollution	Mercury			Ecotoxic emissions	1.97×10^2
	Cadmium	Carcinogenic effects	7.12×10^{-2}	Ecotoxic emissions	4.80×10^2
	Hexavalent Chromium	Carcinogenic effects	3.43×10^{-1}		
	Lead			Ecotoxic emissions	7.39
	Arsenic	Carcinogenic effects	6.57×10^{-2}	Ecotoxic emissions	11.4
	Volatile phenol	Carcinogenic effects	1.05×10^{-5}		
	Cyanide	Carcinogenic effects	4.16×10^{-5}		
	Oil	Carcinogenic effects	4.16×10^{-5}		

3.3. Emergy Accounting of Beijing Socio-Economic System

Examination of various aspects of the Beijing economy includes a discussion of Beijing's emergy resources, emergy consumption patterns, emergy conservation, and emergy yields. The results in 2006 are shown in the Appendix. In accordance with the system picture of Beijing (see Figure 3) and the consequent calculations shown in the Appendix, main flows introduced to the Beijing urban socio-economic system for the studied years are summarized in Table 2.

3.3.1. Emergy Inflows in Beijing Socio-Economic System

Since 1999, Beijing as the capital of China has adhered to the policy of reform and opening-up, and focused on economic construction. Gradually, it has stepped onto the road of establishing a market-oriented economy system. As a result, the consumption of energy, material and labors increased correspondingly. Total emergy actually used (U), as potential investment in emergy yield of the city, increases with an annual average of 19.88% with a peak in 2004 (25.11%).

As the primary impetus for the economy, environmental free renewable resources (R) involving sunlight, rain, wind, and geothermal heat remains approximately unchanged at this temporal scale (Figure 4). For the Beijing economy, the specific flow of the geothermal heat with emergy is much more than that from the sunlight, wind and rain. It is worth noticing that, of all the renewable inputs, only the largest item, rain, is taken into account though all the emergy inputs are estimated to avoid

double-accounting, see Appendix. Participation of non-renewable emergy flows from urban local sources (*N*) fluctuated in this period so that the obvious fluctuation in constructed local input includes limestone, sand and gravel and iron ore. Construction materials are the largest individual *N* flows, which is much more than the natural topsoil losses for plant growing and from the degraded soil erosion.

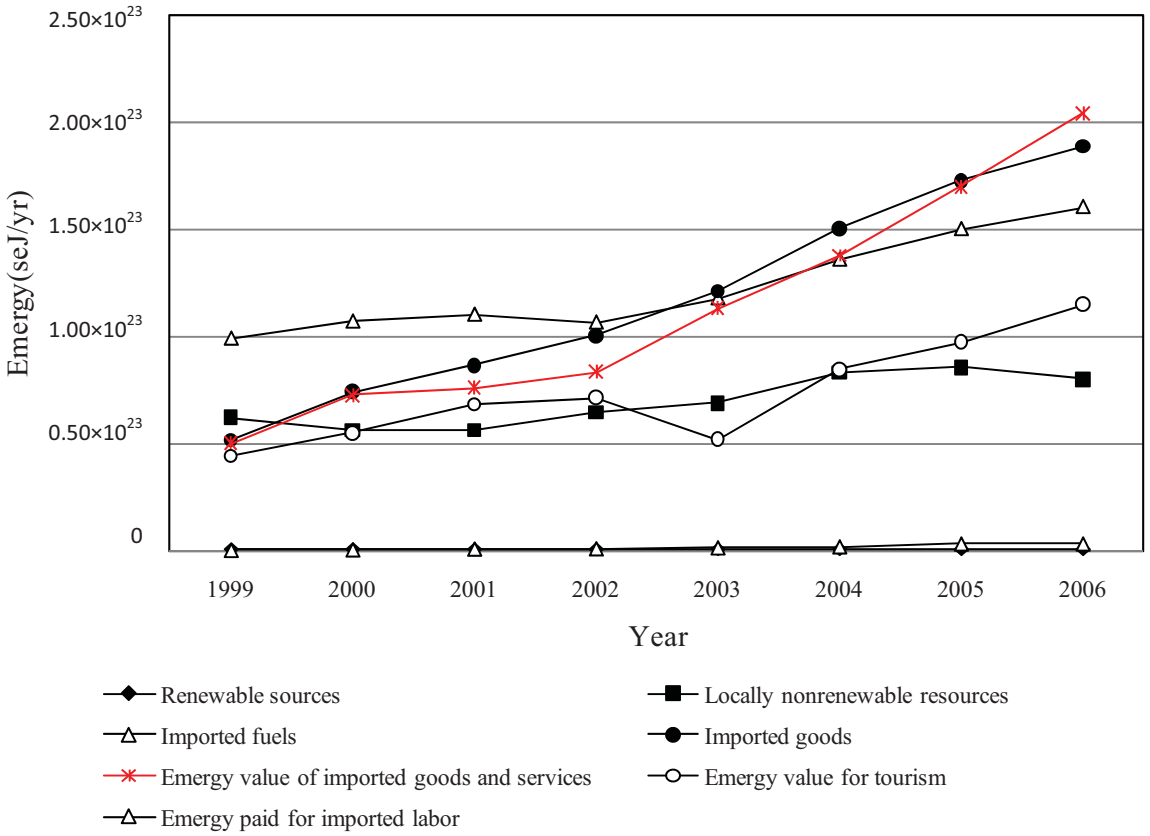
Table 2. Comparison of main emergy indexes and flows for time series emergy synthesis of Beijing.

Variable	Item	Unit	2000	2002	2004	2006
POP	People supported	Unit	1.36×10^7	1.42×10^7	1.49×10^7	1.58×10^7
GDP	Gross domestic product	\$/yr	3.00×10^{10}	3.88×10^{10}	5.17×10^{10}	1.01×10^{11}
R	Renewable sources	seJ/yr	1.05×10^{21}	1.05×10^{21}	1.03×10^{21}	1.03×10^{21}
$N_0 + N_{1F} + N_{1M}$	Locally nonrenewable resources	seJ/yr	5.65×10^{22}	6.48×10^{22}	8.34×10^{22}	8.04×10^{22}
$N_{2F} + N_{2M}$	Imported fuels and minerals (from other provinces)	seJ/yr	1.04×10^{23}	1.07×10^{23}	1.25×10^{23}	1.45×10^{23}
$N_{3F} + N_{3M}$	Imported fuels and minerals (from other countries)	seJ/yr	1.26×10^{20}	2.28×10^{20}	5.95×10^{21}	7.19×10^{21}
G_1	Imported goods (from other provinces)	seJ/yr	4.69×10^{22}	6.71×10^{22}	9.54×10^{22}	1.19×10^{23}
G_2	Imported goods (from other countries)	seJ/yr	2.76×10^{22}	3.39×10^{22}	5.56×10^{22}	6.95×10^{22}
$I_{11} + I_{12} + I_{13}$	Dollars paid for imports goods (from other provinces)	\$/yr	1.28×10^{10}	1.50×10^{10}	2.44×10^{10}	3.61×10^{10}
$I_{21} + I_{22} + I_{23}$	Dollars paid for imports goods (from other countries)	\$/yr	7.55×10^9	7.60×10^9	1.42×10^{10}	2.10×10^{10}
I_3	Dollars for tourism	\$/yr	1.10×10^{10}	1.43×10^{10}	1.70×10^{10}	2.30×10^{10}
I_4	Dollars paid for imported labor	\$/yr	1.89×10^8	2.88×10^8	4.67×10^8	7.30×10^8
$P_3 (I_{11} + I_{12} + I_{13})$	Emergy value of imported services (from other provinces)	seJ/yr	4.59×10^{22}	5.56×10^{22}	8.72×10^{22}	1.29×10^{23}
$P_2 (I_{21} + I_{22} + I_{23})$	Emergy value of imported services (from other countries)	seJ/yr	2.69×10^{22}	2.81×10^{22}	5.08×10^{22}	7.51×10^{22}
P_3I_2	Emergy value for tourism	seJ/yr	5.52×10^{22}	7.17×10^{22}	8.50×10^{22}	1.15×10^{22}
P_3I_3	Emergy paid for imported labor	seJ/yr	9.43×10^{20}	1.44×10^{21}	2.33×10^{21}	3.65×10^{21}

The Appendix also lists main imported inputs in terms of emergy flows for 2006 in Beijing. The total imports increased from 1.51×10^{23} to 3.49×10^{23} seJ/yr. Of the total imported resources, fuels grew by 1.52-fold, with emergy rising from 8.84×10^{22} to 1.35×10^{23} seJ/yr, while the total imported building materials (including iron ores, sand and gravel, iron and steel) increased by 3.92-fold from 4.32×10^{22} to 1.70×10^{23} seJ/yr. This indicates that Beijing's economic development is increasingly dependent on the infrastructure construction, which has even replaced the fuel-consuming industry for nearly a decade. In emergy to money terms, imported goods have become the most important item in this category. The export emergy flows could be highlighted petroleum derived products, minerals and mechanical and transport equipment. As shown in Figure 4, the service associated with imports in Beijing was a total of 2.04×10^{23} seJ/yr in 2006, 4.04 times more than that in 1999. This increase in import results in decreased self-sufficiency, so the purchased component of the total economy was

more important, supporting the growth of the economy. The services imported from other provinces were 7.6 times more than that from abroad, indicating that the imports of Beijing were still increasingly dependent upon the transmission of domestic market. And it's worth mentioning that, in emergy to money terms, the tourism and emergy paid for imported labor are increasing strongly, more than 2.58 and 5.52 times respectively.

Figure 4. Temporal variations of emergy inflows in Beijing socio-economic system during concerned period of 1999–2006.



3.3.2. The Components of the Energy Consumed in Beijing

The Appendix and Table 2 give detailed information on the consumption of energy by source for Beijing from 1999 to 2006. During this period, coal was still the most primary energy source for the region, as measured by both heat content and emergy. The coal input decrease from 2000 is evident in the figure, but this was followed by a rapid rebound over the next three years when Beijing won the bid to stage the 2008 Olympiad. Meanwhile, the consumption of petroleum from other provinces steadily decreased; however, the imported oil increases along with coal consumption in these ten years. Imported electricity is a large fraction of the total emergy use (11% to 13%) that grew fast from 1999 to 2006. During the decade, exported electricity in these years remained low. Natural gas also became the fourth largest energy source. The consumption of natural gas showed a similar trend to that of imported electricity, but with a damped response to fluctuations.

3.3.3. Mineral Use in Beijing

The emergy of iron and steel made the largest contribution to the emergy of minerals consumed followed by the emergy of lead up to 1999, when it was overtaken by the emergy of sand and gravel for construction. Compared with sand and gravel, hi-tech products, machinery and electrical equipment increased greatly from 1999 to 2006 and it consistently occupied the position of the 3rd largest emergy input after labor and services.

3.4. The Human Capital and Natural Capital Losses

From 1999 to 2006, the total human capital losses caused by the six air pollutants increased dramatically from 4.17×10^{20} to 1.15×10^{21} seJ/yr and reached a maximum peak of 1.31×10^{21} seJ/yr in 2005 (Table 3), while losses due to the urban production sectors fluctuated with a maximum at 1.70×10^{21} seJ/yr in 2005, as shown in Table 3. The natural capital losses showed that such losses, different from human capital losses, were assessed on the basis of acidification and ecotoxicologic emissions. The loss due to NO_x shows a very large increase in the investigated period, especially after 2004. Results seem to suggest that NO_2 has overtaken SO_2 as the ever-bigger issue in Beijing's environmental pollution treatment during 1999–2006. The growth rate of damage that is caused by the emissions from urban consumption processes climbs up faster. Nitrogen dioxide and sulfur dioxide provided the largest contribution to natural capital loss while the greenhouse gases (CO_2) and dust play the larger role in human capital loss.

Table 3. Indirect emergy input associated to emissions (Unit: seJ/yr).

Emissions	2000		2002		2004		2006	
	Human Capital Losses	Natural Capital Losses	Human Capital Losses	Natural Capital Losses	Human Capital Losses	Natural Capital Losses	Human Capital Losses	Natural Capital Losses
CO_2	3.98×10^{20}		4.40×10^{20}		7.36×10^{20}		7.82×10^{20}	
CO	0		0		0		0	
NO_x	2.03×10^{20}	1.79×10^{21}	2.98×10^{20}	2.04×10^{21}	3.03×10^{20}	1.39×10^{21}	6.16×10^{20}	2.65×10^{21}
SO_2	3.96×10^{20}	1.03×10^{21}	3.46×10^{20}	7.02×10^{20}	3.13×10^{20}	4.23×10^{20}	2.85×10^{20}	3.62×10^{20}
TSP	7.04×10^{20}		6.92×10^{20}		1.19×10^{21}		8.90×10^{20}	
N_2O	2.27×10^{18}		2.57×10^{18}		4.45×10^{18}		4.97×10^{18}	
CH_4	1.26×10^{18}		1.51×10^{18}		2.43×10^{18}		2.72×10^{18}	
Mercury	0	0	0	0	0	0	0	0
Cadmium	0	0	0	0	0	0	4.23×10^{15}	1.90×10^{15}
Hexavalent chromium	2.03×10^{18}		7.53×10^{17}		1.22×10^{18}		9.27×10^{17}	
Lead	0	8.00×10^{15}	0	3.46×10^{15}	0	1.12×10^{15}	0	3.07×10^{14}
Arsenic	6.50×10^{16}	1.54×10^{15}	0	0	0	0	0	0
Volatile phenol	1.66×10^{15}		3.46×10^{14}		1.34×10^{14}		2.42×10^{14}	
Cyanide	3.29×10^{15}		9.14×10^{14}		3.74×10^{14}		1.24×10^{14}	
Oil	3.70×10^{17}		2.28×10^{17}		1.54×10^{17}		8.99×10^{16}	
$L_{w,1}^*$	1.71×10^{21}		1.78×10^{21}		2.55×10^{21}		2.58×10^{21}	
$L_{w,2}^*$	2.82×10^{21}		2.74×10^{21}		1.81×10^{21}		3.01×10^{21}	
$L_{w,3}$	1.54×10^{19}		1.87×10^{19}		3.96×10^{19}		4.98×10^{19}	

Note: $L_{w,1}^*$ is emergy of the human life losses caused by the emissions; $L_{w,2}^*$ is emergy of the ecological losses due to the emissions; $L_{w,3}$ is emergy of the land occupation caused by the emissions.

3.5. Analysis of the Emergy Indicators for Beijing

In this section, a series of emergy indicators based on the emergy accounting for Beijing economy are analyzed, discussed and compared with those of other Chinese cities. These indicators lend insight to the emergy support basis, the economic structure and the characters of the Beijing economy.

3.5.1. Emergy Intensity

Empower density or the emergy flow per unit area is a related measure that indicates the spatial concentration of economic activity or the intensity of development in a city. As shown in Table 4, the empower density of the Beijing economy developed from 1.85×10^{13} seJ/m^2 in 1999 to 4.59×10^{13} seJ/m^2 in 2006, revealing that Beijing maintained a rapid economic growth and scored a new high in economic aggregates during the past years. Accounting results shows that this growth was mainly caused by the input from goods and services which hold relatively high emergy transformity. Combined with the emergy use structure and the value of emergy use per person in Beijing, we find that of the total resource consumed in Beijing, most is correlated with goods and services purchased from outside, with little from free natural inputs. It also means that the development both in the living standard of local residents and in urban economy depends completely on the purchase of resources from outside.

Table 4. The integrated emergy indicator of Beijing.

Variable	Item	Unit	2000	2002	2004	2006
U	Total emergy used	seJ/yr	3.68×10^{23}	4.30×10^{23}	5.96×10^{23}	7.53×10^{23}
ED	Empower density	seJ/m^2	2.19×10^{13}	2.56×10^{13}	3.63×10^{13}	4.59×10^{13}
U/POP	Use per person	seJ/ pop	2.71×10^{16}	3.02×10^{16}	4.00×10^{16}	4.76×10^{16}
ELR	Environmental loading ratio		3.48×10^{2}	4.07×10^{2}	5.78×10^{2}	7.31×10^{2}
EYR	Net emergy yield ratio		1.19	1.18	1.16	1.12
ESI	Environmental sustainability index		3.40×10^{-3}	2.90×10^{-3}	2.01×10^{-3}	1.53×10^{-3}

Note: $U = R + N_{2F} + N_{2M} + N_{3F} + N_{3M} + G_1 + G_2 + P_3 (I_{11} + I_{12} + I_{13}) + P_2 (I_{21} + I_{22} + I_{23}) + P_3I_2 + P_3I_3 + N_0 + N_{1F} + N_{1M}$; ED = U/area; ELR = $(N_{2F} + N_{2M} + N_{3F} + N_{3M} + G_1 + G_2 + P_3 (I_{11} + I_{12} + I_{13}) + P_2 (I_{21} + I_{22} + I_{23}) + P_3I_2 + P_3I_3 + N_0 + N_{1F} + N_{1M} + L_{w,1}^* + L_{w,2}^* + L_{w,3})/(R + P_3 (I_{11} + I_{12} + I_{13}) + P_2 (I_{21} + I_{22} + I_{23}))$; EYR = $(U + L_{w,1}^* + L_{w,2}^* + L_{w,3})/(N_{2F} + N_{2M} + N_{3F} + N_{3M} + G_1 + G_2 + P_3 (I_{11} + I_{12} + I_{13}) + P_2 (I_{21} + I_{22} + I_{23}) + P_3I_2 + P_3I_3 + L_{w,1}^* + L_{w,2}^* + L_{w,3})$; ESI = EYR/ELR.

3.5.2. Import/Export Structure

For an urban ecosystem, the emergy welfare enjoyed by its residents also can be revealed by comparing the resource imports and exports, which are accounted through two ratios here, one is the difference between exports and imports; the other is exports to imports. From 1999 to 2006, the exports/imports ratio of Beijing is less than 1. During this period, the rapid development of Beijing industry brought about a quick need for energy, which made the fuel consumption increase from 1.01×10^{23} seJ in 1999 to 1.90×10^{23} seJ in 2006. Most of these fuels are used by industry, construction and transportation. In this period, the imported emergy was much more than the exported emergy with the largest difference appearing in 2005 and 2006.

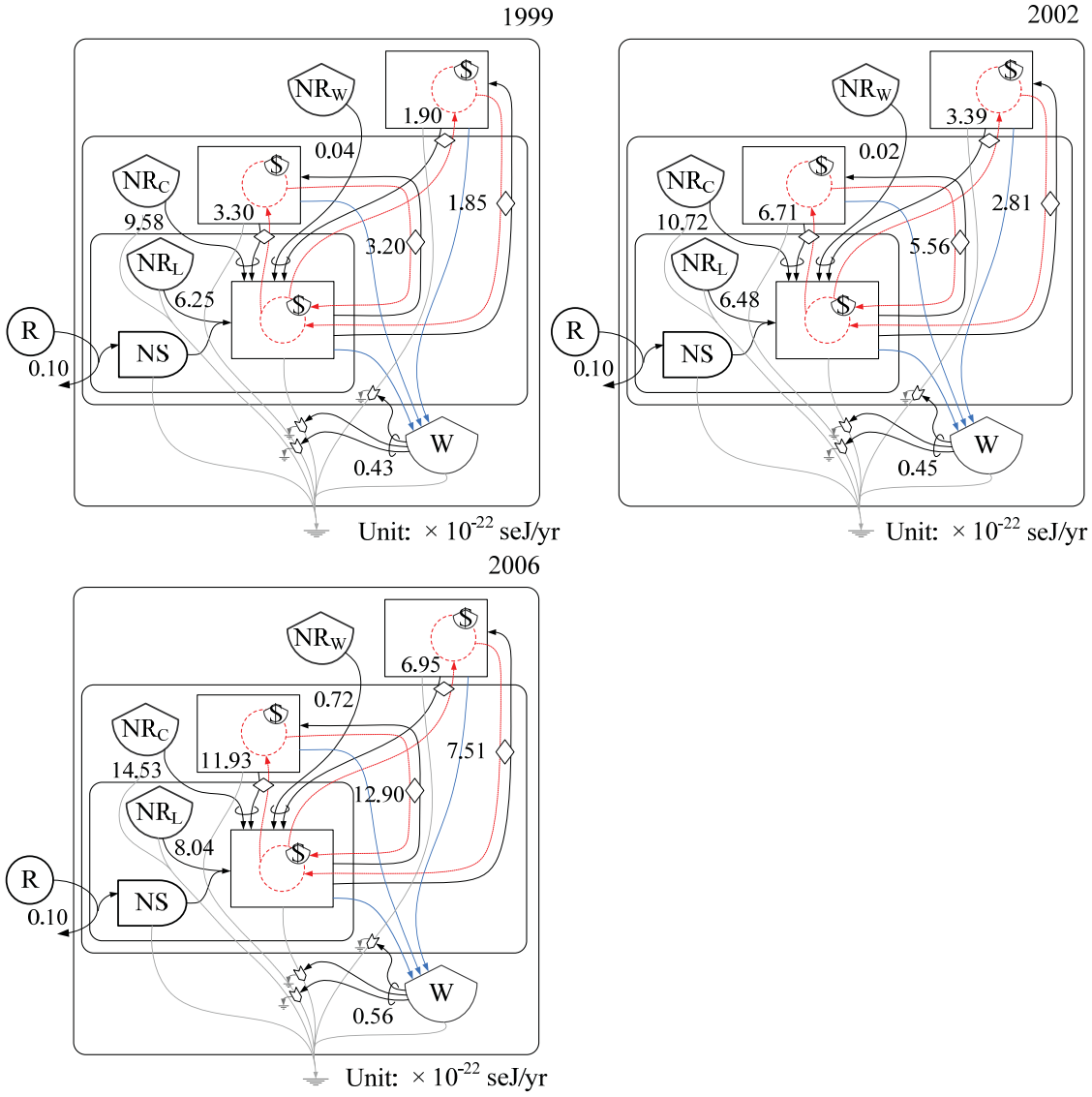
3.5.3. Environmental Sustainability Index

This index is an aggregate measure of the economic benefit (EYR) per unit of environmental loading (ELR). It shows that the long-term capacity of the renewable emergy sources to support life is being degraded. A quick estimate of the renewable carrying capacity of a state at the current standard of living is obtained by multiplying the fraction of use that is renewable by the present population of the state [22]. As a consequence of EYR and ELR trends, the sustainability index ESI dropped significantly, thus suggesting that emissions greatly reduced the sustainability of the urban socio-economic system by pulling resources for damage repair and for replacement of lost natural and human-made capital.

3.6. Emergy-Based Multiple Spatial Scale Analysis of Beijing Socio-Economic System

We modeled the interaction of economic activities with environmental resources as a production function situated at the interface between the environment and society in cross-hierarchy perspective. Minerals, fuels, natural products as timber, water and human labor, are all required emergy inputs from different regions that support economic activities. Meanwhile, the conceptual model also showed that the environment provides emergy to support society as a whole and the emissions have the direct and indirect impacts on the economic production function on all urban, country and global scales. The multiple spatial scale analysis separates inflow and outflow, which are ordered into societal assets and structures. Indeed, when materials and emergy were placed on an equal basis using emergy, we found that materials (steel and iron, *et al.*) from local and other provinces in China were the dominant input to Beijing's economy during the period considered. Thus, it is plausible that the total emergy used by a prosperous city, which takes into account the materials as well as the energy used, might explain more of the variance of economic activity than energy alone. If mass alone was used as the measure of relative importance, the construction materials, sand and gravel and crushed stone would dominate the signature of inputs to the Beijing's economy by an order of magnitude. However, when specific emergies are used to transform the mass inputs to emergy, the picture of the relative importance of materials is very different. Construction materials are still the largest input at times, but other unexpected materials show their strategic importance when converted to emergy. Except for iron ore and steel, from the 1999 to the 2006, purchased/traded commodities including hi-tech products, machinery and electrical equipments from other provinces in China was the third largest contributor of emergy to the urban system. But the growth of traded rate from other countries is much slower than that from other provinces. As Figure 5 shows, emergy flows from the national system are 52.7 times higher than those from the world system in 2006. Also the emergy values are much more than that returned via monetary transactions. This way of illustrating net emergy flows is also possible to be applied to regional relations in general. From another point of view, the multi-scale environmental impacts of waterborne and airborne pollutions continue increasing from 1999 to 2006 and the values cannot be neglected.

Figure 5. Diagrams of emergy cross-hierarchy inflows in different years. Note: R is renewables; NS is local natural system; NR_L is local Non-renewables; NR_C is Non-renewables from other provinces; NR_W is Non-renewables from other countries; W is waste emissions.



As illustrated in Figure 5, denser flows of emergy move from left to right than what is fed back via monetary transactions, hence resulting in a net accumulation in the global system. In addition, this unfair exchange is self-reinforcing due to neo-colonial controls. Therefore, the distribution of resources and wealth can never be fully understood without explicit emphasis on power relations and fairness. In this figure, control resulting from such power relations is represented by the pathway line moving from right to left. So as long as there is trade, a part of the regions will specialize in resource-intensive production. In that case, in a prosperous city, such as Beijing, the urban consumption demand will shift to other regions and increase their production, which includes the shift of environmental impacts. If resources intensity of these regions is lower than others, then global emissions will decrease. On the contrary, other regions' resource use reduction will even increase global emissions. In

this sense, a more systematic consumption-based approach, which can eliminate pollution leakage and encourage reductions to occur where the costs are the lowest, will be more favorable. Thus, given the structure of input, Beijing was chiefly making greater profits by shifting resources from other provinces in China and transferring the emissions outside.

4. Conclusions

Increasing interest among the general public in reducing environmental impacts has fueled the aspiration of eco-cities to achieve healthy status. This study contributes to the current body of relevant literature by exploring Beijing's organizational structure of the socio-economic system. Our research focused on the characteristics of the interface in Beijing between different scales based on an emergy synthesis approach, in order to highlight the resource trade and environmental impact and separate the inwards/outwards flow, economic and ecological losses between different scales. Clarifications regarding the emissions scope and system boundaries are essential in order to develop a strategy for monitoring the intimate relationship between the resource base and economic structure. Detailed trends of the resource base and performance indicators are examined from a historical perspective for the contemporary Beijing urban system after China's Economic Reform and Opening Policies in the latest decade.

The results demonstrated that the development of economy in Beijing was closely correlated with the consumption of the nonrenewable resources and exerts rising pressure on the environment. Of the total emergy use by the economic system, the imported nonrenewable resources from other provinces contribute the most, with increasing use of imported nonrenewable resources. The multi-scale environmental impacts of waterborne and airborne pollutions continue to increase from 1999 to 2006.

Considering the structure of inputs, Beijing was chiefly making greater profits by shifting resources from other provinces in China and transferring the emissions outside. Our findings suggested several policy implications, assuming the goal is to achieve urban ecosystem health. In this regard, a regional emission trade scheme (ETS) should be enacted in the Chinese market system, via which the eastern developed regions (such as Beijing) could buy emissions directly from the west area via local governmental transactions. Via such an ETS, emissions in the eastern area can be reduced; furthermore the less developed area also benefit from such an emissions trading system. These policies may seem harsh. Curtailing development, trade or limiting access to resources may end up neo-colonial controls. Our message is not to abandon all development, stop all trade and limit resource access, but rather to highlight the limitations and consequences that might result from not taking such actions.

It is in this sense that we see this article as a step along a research path rather than its final statement. Going beyond a conceptual framework, this study specified a detailed list of emissions categories and regarded them as indirect inputs of ecological services for airborne and waterborne pollutants dilution and damage repair or replacement to "internalize" the "externalities" of different scales with emphasis on a joint application of the emergy synthesis. It is expected that such a detailed listing will evolve over time as formal standards are proposed and revised, and as the technical capacity to increase the pollution types and local impacts continues to improve.

Acknowledgements

This work is supported by the National Ministry of Science and Technology (Grant No. 2007BAC28B03), the National Natural Science Foundation of China (Grant No. 40871056), and the National Science Foundation for Distinguished Young Scholars (Grant No. 50625926).

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Appendix

Table A-1. Emergy flows supporting urban socio-economic system in 2006.

	Items	Units	Raw Amount	Transformity (seJ/unit)	Ref. trans.	Emergy (seJ/yr)
Free renewable environmental resources						
1	Sun	J/yr	7.02×10^{19}	1	by definition	7.02×10^{19}
2	Kinetic energy of wind	J/yr	4.87×10^{16}	2.51×10^{3}	[51]	1.22×10^{20}
3	Rainfall (Geopotential Energy)	J/yr	1.25×10^{15}	1.74×10^{4}	[51]	2.19×10^{19}
4	Rainfall (Chemical Potential)	J/yr	1.12×10^{16}	3.05×10^{4}	[51]	3.43×10^{20}
5	Geothermal Heat	J/yr	1.79×10^{16}	5.76×10^{4}	[51]	1.03×10^{21}
Exploited local nonrenewable resources						
6	Top soil loss	J/yr	3.17×10^{14}	1.23×10^{5}	[51]	3.90×10^{19}
7	Coal	J/yr	2.04×10^{17}	6.69×10^{4}	[51]	1.37×10^{22}
8	Minerals					
	Limestone	g/yr	1.52×10^{13}	1.68×10^{9}	[52]	2.55×10^{22}
	Sand and gravel	g/yr	1.02×10^{13}	1.68×10^{9}	[52]	1.70×10^{22}
	Iron ore	g/yr	1.68×10^{13}	1.44×10^{9}	[51]	2.41×10^{22}

Calculations:

1. Sun: average insolation = 5.36×10^9 J/m^2/yr, total area of Beijing region = 1.64×10^4 km^2, continental albedo = 0.201. Solar energy received = (total area of Beijing region) (average insolation) (1 − albedo) = (1.64×10^4 km^2 × 10^6) (5.36×10^9 J/m^2/yr) (1 – 0.201) = 7.02×10^{19} J/yr.

2. Kinetic energy of wind: air density = 1.3 kg/m^3, wind velocity (annual average) = 2.5 m/s, observed winds are about 0.6 of geostrophic wind, drag coefficient = 1.00×10^{-3}, Time frame = $365 \times 24 \times 60 \times 60 = 3.15 \times 10^7$ s/yr. Wind energy = (air density) (drag coeff.) (geostrophic wind velocity)^3 (total area) (time frame) = (1.3 kg/m^3) (1.00×10^{-3}) (2.5 m/s/0.6)^3 (1.64×10^4 km^2 × 10^6) (3.15×10^7 s/yr) = 4.87×10^{16} J/yr.

3. Rainfall (geopotential Energy): total agricultural area of Beijing = 1.64×10^{10} m^2, rain (annual average) = 0.318 m/yr, average elevation = 43.5 m, runoff rate = 56.40%. Energy = (total area) (rainfall) (% runoff) (avg elevation) (gravity) = (1.64×10^4 km^2 × 10^6) (0.318 m/yr) (56.40%) (43.5 m) (9.8 kg/m^2) = 1.25×10^{15} J/yr.

4. Rainfall (chemical potential energy): water density = 1.00×10^6 g/m^3, mass of rainfall water = (rainfall) (total area) (water density) = (0.318 m/yr) (1.64×10^4 km^2 × 10^6) (1.00×10^6 g/m^3) = 5.22×10^{15} g/yr, fraction of water that is evapotranspired = 44%, Gibbs free energy of water = 4.94 J/g. Energy = (evapotranspired water) (Gibbs free energy per gram water) = (5.22×10^{15} g/yr) (44%) (4.94 J/g) = 1.12×10^{16} J/yr.

5. Geothermal heat: average heat flow per area = 3.50×10^{-2} J/m^2/s. Energy = (land area) (heat flow per area) = 1.79×10^{16} J/yr.

6. Net loss of organic matter in topsoil: soil erosion rate = 8.15×10^2 g/m^2/yr, average % organic in soil = 0.02, assuming water content in organic matter = 0.7, energy content of dry organic matter = 5.00 kcal/g. Energy = (total agricultural area) (erosion rate) (% organic) (1 − water content in organic matter) (energy content of dry organic matter) (4186 J/kcal) = (1.64×10^{10} m^2) (8.15×10^2 g/m^2/yr) (0.02) (1 – 0.7) (5.00 kcal/g) (4186 J/kcal) = 3.17×10^{14} J/yr.

7. Fuels input from local region: coal = 6.42×10^6 t/yr, coal energy = (6.42×10^6 t/yr) (3.18×10^{10} J/t) = 2.04×10^{17} J/yr; Oil = 0 t/yr, oil energy = (0 t/yr) (4.30×10^{10} J/t) = 0 J/yr; Natural gas= 0 m^3, natural gas energy = (0 m^3) (0.7174 kg/m^3) = 0 J/yr.

8. Constructed local input: cement quantity of production = 1.27×10^7 t/yr, assuming 1.2 t limestone and 1.6 t sand and gravel are needed to produce 1t cement and 50% of sand and gravel is from local regain, limestone = 1.52×10^{13} g/yr, sand and gravel = 1.02×10^{13} g/yr, iron ore = 1.68×10^7 t = 1.68×10^{13} g/yr.

Table A-2. Emergy imports for urban socio-economic system in 2006.

	Items	Units	Raw amount	Transformity (seJ/unit)	Ref. trans.	Emergy (seJ/yr)
9	Hydroelectricity	J/yr	2.30×10^{14}	3.36×10^{5}	[51]	7.74×10^{19}
10	Stream flow	J/yr	8.81×10^{15}	3.05×10^{4}	[52]	2.69×10^{20}
11	Fuels import					
	Coal	J/yr	7.04×10^{17}	6.69×10^{4}	[51]	4.83×10^{22}
	Coke	J/yr	4.72×10^{16}	1.10×10^{5}	[53]	5.18×10^{21}
	Crude oil	J/yr	3.45×10^{17}	9.08×10^{4}	[53]	3.13×10^{22}
	Gasoline	J/yr	9.20×10^{16}	1.05×10^{5}	[53]	9.64×10^{21}
	Kerosene	J/yr	1.23×10^{17}	1.10×10^{5}	[53]	1.36×10^{22}
	Diesel oil	J/yr	8.61×10^{16}	1.10×10^{5}	[53]	9.48×10^{21}
	Fuel oil	J/yr	4.42×10^{15}	1.10×10^{5}	[53]	4.87×10^{20}
	Liquefied petroleum gas (LPG)	J/yr	6.66×10^{15}	1.11×10^{5}	[53]	7.37×10^{20}
	Natural gas	J/yr	1.58×10^{17}	9.85×10^{4}	[54]	1.56×10^{22}
12	Electricity	J/yr	1.47×10^{17}	1.74×10^{5}	[51]	2.57×10^{22}
13	Imported goods					
13.1	Imported food, livestock and products					
	Grain	J/yr	1.91×10^{16}	1.14×10^{5}	[55]	2.18×10^{21}
	Rapeseed	J/yr	8.23×10^{16}	8.88×10^{4}	[56]	7.31×10^{21}
	Vegetable	J/yr	1.42×10^{14}	7.37×10^{4}	[56]	1.05×10^{19}
	Fruit	J/yr	2.30×10^{13}	8.88×10^{4}	[57]	2.04×10^{18}
	Meat	J/yr	2.75×10^{9}	5.31×10^{6}	[55]	1.46×10^{16}
	Milk	J/yr	2.36×10^{11}	3.35×10^{6}	[55]	7.90×10^{17}
13.2	Imported raw and processed materials					
	Wood	J/yr	1.51×10^{15}	5.36×10^{4}	[51]	8.11×10^{19}
	Iron ores	g/yr	4.68×10^{13}	1.44×10^{9}	[51]	6.72×10^{22}
	Sand and gravel	g/yr	1.02×10^{13}	1.68×10^{9}	[52]	1.70×10^{22}
	Paper and paperboard	J/yr	1.20×10^{15}	7.37×10^{4}	[58]	8.85×10^{19}
	Silk	J/yr	6.39×10^{11}	1.12×10^{7}	[51]	7.18×10^{18}
	Wool, animal hair	J/yr	1.32×10^{14}	7.37×10^{6}	[51]	9.70×10^{20}
13.3	Imported goods					
	Polythene (PE)	g/yr	7.30×10^{10}	4.69×10^{9}	[59]	3.43×10^{20}
	Polypropylene(PP)	g/yr	1.60×10^{10}	4.69×10^{9}	[59]	7.51×10^{19}
	Polystyrene (PS)	g/yr	1.10×10^{10}	4.69×10^{9}	[59]	5.16×10^{19}
	Other coke chemicals	g/yr	2.54×10^{10}	4.89×10^{9}	[59]	1.24×10^{20}
	Other petroleum products	g/yr	1.16×10^{12}	4.89×10^{9}	[59]	5.69×10^{21}
	Iron and steel	g/yr	2.70×10^{13}	3.16×10^{9}	[60]	8.53×10^{22}
	Aluminum and articles	g/yr	1.20×10^{12}	7.74×10^{8}	[51]	9.29×10^{20}
13.4	Other metals and articles	g/yr	2.16×10^{11}	4.74×10^{9}	[51]	1.02×10^{21}
13.5	Hi-tech products, machinery and electrical equipment					
	Steel	g/yr	3.65×10^{9}	3.16×10^{9}	[60]	1.15×10^{19}
	Aluminum	g/yr	1.65×10^{9}	7.74×10^{8}	[51]	1.28×10^{18}
	Copper	g/yr	1.20×10^{9}	3.36×10^{9}	[59]	4.05×10^{18}
	Other metals	g/yr	4.20×10^{9}	4.74×10^{9}	[51]	1.89×10^{19}
	Ceramics/Glasses	g/yr	1.69×10^{10}	3.18×10^{9}	[59]	5.37×10^{19}
	Plastics	g/yr	6.09×10^{9}	7.21×10^{9}	[51]	4.39×10^{19}

Table A-2. *Cont.*

	Items	Units	Raw amount	Transformity (seJ/unit)	Ref. trans.	Emergy (seJ/yr)
13.6	Transport equipment					
	Steel	g/yr	1.88×10^{10}	3.16×10^{9}	[60]	5.94×10^{19}
	Aluminum	g/yr	3.21×10^{9}	7.74×10^{8}	[51]	2.48×10^{18}
	Rubber and plastic material	g/yr	2.29×10^{8}	7.21×10^{9}	[51]	1.65×10^{18}
	Copper	g/yr	6.87×10^{8}	3.36×10^{9}	[59]	2.31×10^{18}
13.7	Electronic goods (estimated from component materials)					
	Ferrous metal	g/yr	1.25×10^{9}	3.16×10^{9}	[60]	3.94×10^{18}
	Silica/glass	g/yr	1.62×10^{9}	3.18×10^{9}	[51]	5.16×10^{18}
	Copper	g/yr	4.36×10^{8}	3.36×10^{9}	[59]	1.47×10^{18}
	Plastics	g/yr	1.43×10^{9}	7.21×10^{9}	[51]	1.03×10^{19}
	Aluminum	g/yr	8.72×10^{8}	7.74×10^{8}	[51]	6.75×10^{17}
	Other metal	g/yr	4.98×10^{8}	4.74×10^{9}	[51]	2.36×10^{18}
14	Imported human labor (commuters)	\$/yr	7.30×10^{8}	5.00×10^{12}	This study, country emergy/\$ ratio	3.65×10^{21}
15	Services associated to imports					
	From other provinces	\$/yr	1.80×10^{10}	5.00×10^{12}	This study, country emergy/\$ ratio	9.02×10^{22}
	Import	\$/yr	1.05×10^{10}	1.13×10^{12}	This study, world emergy/\$ ratio	1.19×10^{22}
	Size of specific sectors					
16	Tourism	\$/yr	2.30×10^{10}	5.00×10^{12}	This study, country emergy/\$ ratio	1.15×10^{23}

Calculations:

9. Hydroelectricity: Hydroelectricity = 6.40×10^{7} kwh/yr. Energy = (6.40×10^{7} kwh/yr) (3.60×10^{6} J/kwh) = 2.30×10^{14} J/yr.

10. Stream flow: upstream inflow = 1.78×10^{9} m^3/yr, coefficient = 4.94×10^{6} J/m^3. Energy = (upstream inflow) (coefficient) = (1.78×10^{9} m^3/yr) (4.94×10^{6} J/m^3) = 8.81×10^{15} J/yr.

11. Fuel imports: coal = 2.68×10^{7} t/yr, coal energy = (2.68×10^{7} t/yr) (3.18×10^{10} J/t) = 7.04×10^{17} J/yr; coke = 1.66×10^{6} t/yr, coke energy = (1.66×10^{6} t/yr) (2.85×10^{10} J/t) = 4.72×10^{16} J/yr; crude oil = 8.09×10^{6} t/yr, oil energy = (8.09×10^{6} t/yr) (4.30×10^{10} J/t) = 3.45×10^{17} J/yr; gasoline = 1.97×10^{6} t/yr, gasoline energy = (1.97×10^{6} t/yr) (4.67×10^{10} J/t) = 9.20×10^{16} J/yr; kerosene = 1.23×10^{17} t/yr, kerosene energy = (1.23×10^{17} t/yr) (4.30×10^{10} J/t) = 1.23×10^{17} J/yr; diesel oil = 2.00×10^{6} t/yr, diesel oil energy = (2.00×10^{6} t/yr) (4.30×10^{10} J/t) = 8.61×10^{16} J/yr; fuel oil = 1.04×10^{5} t/yr, fuel oil energy = (1.04×10^{5} t/yr) (4.26×10^{10} J/t) = 4.42×10^{15} J/t;

LPG = 1.56×10^5 t/yr, LPG energy = (1.56×10^5 t/yr) (4.26×10^{10} J/t) = 6.66×10^{15} J/t; natural gas = 4.06×10^9 m^3, natural gas energy = (4.06×10^9 m^3) (3.89×10^7 J/m^3) = 1.58×10^{17} J/yr.

12. Electricity: electricity = 4.10×10^{10} kwh/yr. Energy = (4.10×10^{10} kwh/yr) (3.60×10^6 J/kwh) = 1.47×10^{17} J/yr.

13.1. Imported food, livestock and products: grain = 1.32×10^6 t/yr, grain energy = (1.32×10^6 t/yr × 1000) (1.45×10^7 J/kg) = 1.91×10^{16} J/yr; rapeseed = 3.29×10^6 t/yr, rapeseed energy = (3.29×10^6 t/yr × 1000) (2.50×10^7 J/kg) = 8.23×10^{16} J/yr; vegetable = 1.01×10^4 t/yr, vegetable energy = (1.01×10^4 t/yr × 1000) (1.41×10^7 J/kg) = 1.42×10^{14} J/yr; fruit = 1.00×10^4 t/yr, fruit energy = (1.00×10^4 t/yr × 1000) (2.30×10^6 J/kg) = 2.30×10^{13} J/yr; meat = 3.94×10^2 t/yr, meat energy = (3.94×10^2 t/yr × 1000) (6.99×10^6 J/kg) = 2.75×10^9 J/yr; milk = 8.04×10^4 t/yr, milk energy = (8.04×10^4 t/yr × 1000) (2.93×10^6 J/kg) = 2.36×10^{11} J/yr.

13.2. Imported raw and processed materials: wood = 1.89×10^5 m^3/yr, wood energy = (1.89×10^5 m^3/yr) (8.00×10^9 J/m^3) = 1.51×10^{15} J/yr; Iron ores, sand and gravel are from; paper and paperboard = 6.00×10^7 t/yr, paper and paperboard energy = (6.00×10^7 t/yr) (2.00×10^7 J/t) = 1.20×10^{15} J/yr; silk = 3.40×10^7 kg/yr, silk energy = (3.40×10^7 kg/yr/1000) (1.88×10^7 J/t) = 6.39×10^{11} J/yr; wool, animal hair = (7.00×10^6 t/yr) (1.88×10^7 J/t) = 1.32×10^{14} J/yr.

13.3. The weight data of imported goods including polythene (PE), polypropylene (PP), polystyrene (PS), other coke chemicals, other petroleum products, iron and steel, aluminum and articles are collected from [47].

13.4. The weight data of other metals and articles are collected from [47].

13.5.–13.7. The weight data of hi-tech products, machinery and electrical equipment including steel, aluminum, copper, other metals, ceramics/glasses, plastics, transport equipment including steel, aluminum, rubber and plastic material, copper, computer technology including ferrous metal, silica/glass, copper, plastics, aluminum and other metals are collected from [61].

14.–16. The currency data of import human labor, services and tourism are from [47].