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Emergy-based sustainability assessment of Inner Mongolia

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Abstract: An integrated environmental accounting of the Inner Mongolia Autonomous Region (IMAR) is presented in this paper based on emergy analysis with data from 1987 to 2007. Through calculating environmental and economic inputs and a series of emergy indicators, this paper discusses IMAR's resource use structure, economic situation, and trade status. The results show that more than 85% of the emergy used in IMAR was derived from home sources, indicating a strong capacity for self-sufficiency. Concentrated-used local non-renewable emergy, which provides IMAR economy with most of the driving forces, took the largest share in total emergy use after 2004 and reached 58% in 2007. The Western China Development Plan of 2000 ushered in a rapid growth of coal and electricity production and exportation to other regions of China from IMAR. The export/import emergy ratio of IMAR reached 3.46 in 2007, with the coal exported (3.44×10^{23} sej in 2007) without being used by IMAR itself, accounting for almost 100% of the difference between the imports and exports. The results also show that from 1987 to 1998, EmSI values remained higher than 10, suggesting underdevelopment in IMAR; after 1998, EmSI values decreased sharply from 19.07 in 1998 to 1.88 in 2007, indicating that IMAR is characterized by medium-run sustainability and is relying more on non-renewable resources and imports.

Keywords: emergy; resources; sustainability; Inner Mongolia

1 Introduction

"Emergy, spelled with an 'm', is a universal measure of real wealth of the work of nature and society made on a common basis". Emergy analysis normalizes all products and services to equivalents of one form of energy – solar emergy – that enables all of these resources to be compared on a common basis (Odum, 1996). Emergy analysis is an eco-centered valuation method that compensates for the inability of money and traditional embodied energy

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analysis (Brown and Herendeen, 1996) to fairly assess the true, total value of various products, and services.

Economic prosperity is dependent not only on contributions from various goods and services, as traditionally valued, but also on various environmental resources that would otherwise be either discounted or ignored completely. Specifically, the most common traditional metrics for large-scale economic accounting, such as gross domestic production (GDP), exclude the often numerous environmental contributions to economic development. Emergy syntheses can be used to assess the complex relationships of economic and ecological systems and to estimate their long-term sustainability. Such techniques are essential for properly valuing the contribution of nature to all human economic activities and for meeting the demands of sustainable development (Hau and Bakshi, 2004).

The WCED defines “sustainable development” as “development that meets the needs of the present generations without compromising the ability of future generations to meet their own needs (WCED, 1987). Hu (1996) argued that in order to realize the aims of the sustainable development, an integrated development model of the “ecology-centered theory” of the human race-organism-environment interaction-eco-development model should be taken. According to the emergy theory (Brown and Ulgiati, 1997), sustainability is determined by yield, renewability of resource utilization, and load on the environment. The emergy indices of percent renewable, emergy yield ratio, and environmental loading ratio can measure these different aspects of sustainability. The Emergy-based Sustainability Index (EmSI), defined as the ratio of the emergy yield ratio to the environmental loading ratio, is an aggregate measure of an economy’s long-term sustainability. Ternary diagrams (Almeida *et al*., 2007; Giannetti *et al*., 2006) were introduced as graphic tools to assist emergy analysis, recognizing and evaluating the resources use structure and sustainability of the system. Emergy-based research at regional, provincial, and national scales has now been performed for many locations, including China, the United States, Italy, and Denmark (Cai *et al*., 2009; Campbell, 2005; Campbell, 2009; Dong *et al*., 2007; Du and Xu, 2006; Li *et al*., 2003a; Li *et al*., 2003b; Liu *et al*., 2008; Pulselli *et al*., 2008; Ulgiati *et al*., 1994; Wu *et al*., 2008; Yang *et al*., 2010; Zhang *et al*., 2009).

Abundant with natural resources, the Inner Mongolia Autonomous Region (IMAR) is China’s third largest province, the largest coal-producing region since 2009, and one of the leading provinces in electricity generation. The Western China Development Plan of 2000 ushered in an economic boom in IMAR, with an average annual growth rate of 19.6% in the real GDP (relative to 1952) from 2000 to 2007 (IMSY, 2010). This is largely due to the west-to-east energy transfer strategy of the plan that provides IMAR with an opportunity for exploitation of mineral resources while addressing energy shortages in eastern China. The output of coal has been increasing continuously and rapidly, with an annual growth rate of 27.9% during the period 2000–2007. The output of coal has been magnified by approximately 12.1 times from 3.41×10^7 tons in 1987 to 35.4×10^7 tons in 2007. The exportation of coal from IMAR to other regions of China reached 17.4×10^7 tons in 2007, which occupied 49% of the total output of coal. In addition, in 2007, IMAR generated over 180 billion kWh of electricity (~99% of which was generated from coal-fired power plants) and delivered over 68 billion kWh to the neighboring provinces. Clearly, the economic growth in IMAR was at the expense of high rates of non-renewable resource consumption, which may cause an adverse effect on IMAR's long-term sustainability. Given the negative byproducts of this strategy, it is a major challenge for policy makers to balance the needs of the human and natural systems in IMAR, via a fair evaluation of the contributions of nature and the economy to human well-being (Gang, 2008; Zhang and Zhang, 2006; Zhang and Yang, 2008).

Limited research using emergy-based environmental accounting in IMAR has already been conducted (Dong *et al.*, 2007; Zhang *et al.*, 2007; Zhang *et al.*, 2008). Emergy accounting is made for the cropping-grazing system as a whole as well as for the cropping and grazing subsystems in IMAR (Zhang, 2007). Dong *et al.* (2007) calculated a series of emergy indicators of IMAR in 2003 to evaluate IMAR's sustainability. Zhang (2008) analyzed developing trend of IMAR system during 1995–2005 based on emergy indicators. In this study, based on continuous data of IMAR from 1987 to 2007, emergy indicators are classified to appraise emergy intensity, economic efficiency and environmental loading of IMAR system and emergy ternary diagram is used to predict the trend of system sustainability and present an updated study of this region.

The objectives of this paper are to: (1) assess the temporal changes of resources use and annual wealth of IMAR during 1987–2007; (2) analyze IMAR's economic efficiency and trade status based on emergy evaluation; and (3) assess the sustainability of IMAR system for its sustainable future. Using data from 1987 to 2007, we present here an accounting with a longer time series and an integrated analysis of sustainability of IMAR system. By achieving these objectives, we specifically quantify and standardize the main fluxes of energy, materials, and money that flow through and within the boundaries of the region, calculate the emergy flow of renewable resources, non-renewable resources, imports, and exports, analyze a series of emergy indicators (Odum, 1996) based on the emergy account such as environmental load ratio (ELR), emergy exchange ratio (EER), emergy dollar ratio (EDR), and emergy yield ratio (EYR), and evaluate IMAR's resource structure and sustainability with the aid of ternary diagrams.

2 Methods

2.1 Study area

IMAR (97°11′20″–126°10′40″E, 37°12′40″–53°12′30″N) is situated in China's northern frontier, covers an area of 1.183×10^6 km^2, and is inhabited by 24.13×10^6 people. The region's topography is dominated by a mid- to low-elevation plateau area, approximately~800 m above sea level. The majority of the area is dominated by a continental, temperate monsoon climate.

IMAR had 102×10^3 km^2 of cultivated land, 574.4×10^3 km^2 of grassland, and 105.1×10^3 km^2 of forests in 2007 (Figure 1). Its grassland area is one-fourth of China's total and its forested area is the second largest among the 31 provinces in China. Its coal reserves, iron ore reserves, and rare-earth resources are known for their massive storages. IMAR also has substantial mineral products such as asbestos, millstones, and mica. The largest rare-earth metal ore deposit in China is found in IMAR, with reserves amounting to 4360 million tons, which is 81.2% of China's total reserves and 54.2% of the world reserves (Xiong and Zhang, 2002). IMAR's mainstream industries spread among energy, metallurgy, agricultural and livestock products, and chemical production.

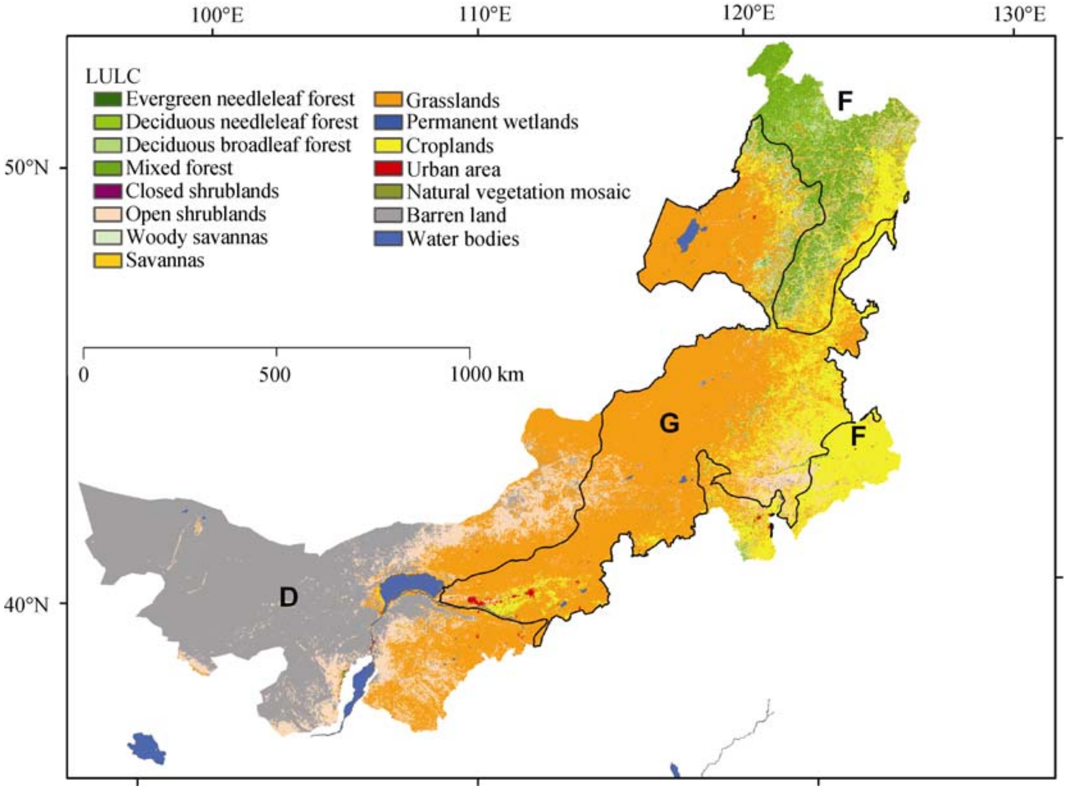

Figure 1 Geographic location of IMAR in East Asia and its land use and land cover (LULC) types using the IGBP's classification system

IMAR acts as an important ecological shelter of northern China. IMAR is ecologically fragile due to its high altitude and latitude, which makes it vulnerable to human activity and climate change (IPCC 2007). Some major environmental challenges facing IMAR include increasing aridity, rangeland degradation, increasing in dust storms, land desertification, soil erosion, reduction in available water resources, and rapid decreases in forest resources. These challenges are all related to its population booming, over-grazing, unsustainable resource use, and the effects of droughts exacerbated by global climate change (Li *et al*., 2008; Lu *et al*., 2008). Historically, managers and policy makers considered significantly fewer problems in evaluating the contributions of natural systems to economic development, which were treated as negative inputs. Remedial measures, such as fencing off for grazing control in degraded grassland areas, have been taken to restore the degradation. However, recent research shows that at least some of these measures may not be very effective to quantify the restoration processes (Han *et al*., 2009). For example, farming and animal husbandry, particularly sheep and goat herding, are the traditional methods of subsistence; yet, the conventional measures do not reflect these practices. Additionally, emphasis on industrial and economic growth during the last two decades has greatly transformed the region and placed an increasing pressure on natural ecosystems. Future management plans are needed to maintain a balance between economic growth and ecosystem stability, which requires an assessment approach for fostering the long-term societal sustainability.

2.2 Emergy synthesis

Emergy synthesis is performed to characterize IMAR as a coupled human and natural system (CHN) in terms of resource use structure, trade status, and sustainability. In emergy analysis, each form of energy, material, or service in the system is translated into solar emergy by way of multiplying units of energy using a conversion factor (i.e., as solar transformity) defined as the solar emergy required to make 1 J of a service or product (sej J^{-1}) (Odum, 1996). Emergy per unit mass of product or emergy per unit of currency is also used (sej g^{-1}, sej $\$^{-1}$), when it is appropriate. Odum, along with others, estimated transformities for various products and services (Bastianoni *et al.*, 2005; Brown and Ulgiati, 1999; Odum, 1996; Odum *et al.*, 2000; Tilley, 1999). The transformities used here have been calculated using the planetary baseline of 15.83×10^{24} sej yr^{-1} (Odum *et al.*, 2000). The annual major emergy that flowed into and out of IMAR includes four accounts: renewable sources, non-renewable resources, imported resources, and exported resources. Raw data of resource flows are translated into solar emergy by multiplying the transformities.

Table 1 is developed to include the summary flows of emergy and money in the IMAR from 1987 to 2007. Sources of emergy from outside include: the renewable resources (R) (i.e., free environmental inputs), imported fuels and minerals (F), goods (G), and the services embodied in these imports (P_2I) (i.e., purchased from economy outside the system). Sources of emergy derived from storages within IMAR include: dispersed rural resources that are used faster than they are renewed, such as soils or forest biomass harvested at unsustainable rates (N_0) and non-renewable resources (i.e., fossil fuels, metals, and minerals) (N_1). Exports from the system include: non-renewable resources (N_2) that are exported without upgrading in the economy, finished products (B), and services and labor (P_1E) embodied in B. The renewable sources are identified as solar radiation, tides, and the deep heat of the earth. In order to avoid double-counting, renewable emergy sources received are defined as the sum of the largest item of each source. Total emergy use (U) in the system is the sum of all of the inputs ($U=R+N_0+N_1+F+G+P_2I$), which reflects the system's annual wealth. An aggregated system diagram for IMAR in 2007 was developed based on the emergy and dollar flows across system boundaries, the interaction of renewable and non-renewable resources within the system, and the exchanges of emergy and dollars that drive the system's economy (Figure 2). We then calculated a series of emergy-based indices (Table 2) based on the flows of energy and products (Table 1). The changes of these indices over time provide us with useful information in identifying the main resources that support quality of life, describe economic efficiency and trade status of IMAR, and estimate the importance of environmental resources on its socioeconomic influences.

Ternary diagrams are used to assess the dependence of the system upon renewable sources (R), non-renewable inputs (N), imported emergy ($F'=F+G+P_2I$; F' is used here for convenience), and to identify and forecast the sustainability of the system. Our emergetic ternary diagram has three components (R, N, F'), with the sum of their fractions equaling 1. These components are represented in an equilateral triangle, with each corner of the triangle representing an element and each side reflecting a binary system. The ternary combinations based on this principle are represented by points within the triangle and the relative proportions of

Table 1 Summary of emergy flows in the IMAR economy (1987–2007)

	Item	Unit	1987	1990	1995	2000	2005	2007
R[a]	Renewable emergy received	sej yr^{-1}	2.779E+23	3.359E+23	3.043E+23	2.542E+23	2.621E+23	2.689E+23
N_0	Dispersed rural source	sej yr^{-1}	8.49E+22	8.49E+22	8.81E+22	9.22E+22	1.01E+23	8.57E+22
N_1	Concentrated use (fuels, etc.)	sej yr^{-1}	9.827E+22	1.198E+23	1.711E+23	1.594E+23	4.613E+23	7.290E+23
N_2	Fuels exported without use	sej yr^{-1}	1.915E+22	3.180E+22	5.609E+22	6.019E+22	2.647E+23	3.748E+23
F	Imported minerals	sej yr^{-1}	1.575E+22	1.674E+22	1.458E+22	5.151E+22	6.826E+22	9.229E+22
G	Imported goods	sej yr^{-1}	1.364E+22	7.964E+21	2.916E+20	3.068E+21	1.218E+22	6.455E+21
P_2I	Imported services, total	sej yr^{-1}	1.109E+22	8.842E+21	1.464E+22	2.542E+22	6.814E+22	7.285E+22
I	Dollars paid for all imports	\$ yr^{-1}	3.369E+08	2.850E+08	7.552E+08	2.070E+09	6.911E+09	9.674E+09
B	Exported prod	sej yr^{-1}	1.418E+22	1.738E+22	1.766E+20	2.325E+22	5.021E+22	8.979E+22
P_1E	Exported services, total	sej yr^{-1}	2.174E+22	2.060E+22	3.496E+22	3.952E+22	9.798E+22	1.476E+23
E	Dollars paid for all exports	\$ yr^{-1}	6.604E+08	6.355E+08	1.803E+09	3.218E+09	9.937E+09	1.960E+10
P_2[b]	China EDR	sej \$$^{-1}$	3.29E+13	3.24E+13	1.94E+13	1.23E+13	1.05E+13	7.53E+12
P_1	IMAR EDR	Sej \$$^{-1}$	1.96E+14	1.49E+14	5.73E+13	3.15E+13	2.01E+13	1.52E+13

[a] R is calculated as the sum of the geo-potential energy of rain and the earth-cycle energy.

[b] The emergy \$$^{-1}$ ratio of China from 1987 to 2005 comes from Z.F. Yang *et al*. (2010), the emergy \$$^{-1}$ ratio of China for 2006 and 2007 are estimated by accounting for China's increased GDP and emergy use since the 2005 value comes from Z.F. Yang *et al*. (2010).

Table 2 The emergy indicators and indices for IMAR (1987–2007)

Name of index	Expression	1987	1990	1995	2000	2005	2007
Non-renewable source flows (sej)	$N= N_0+N_1+N_2$	2.023E+23	2.365E+23	3.153E+23	3.117E+23	8.266E+23	1.190E+24
Imported emergy (sej)	$F+G+P_2I$	4.048E+22	3.354E+22	2.951E+22	8.000E+22	1.486E+23	1.716E+23
Total emergy used (sej)	$U=R+N_0+N+F+G+P_2I$	5.016E+23	5.741E+23	5.930E+23	5.851E+23	9.718E+23	1.255E+24
Exported emergy (sej)	$B+P_1E+N_2$	5.507E+22	6.979E+22	9.122E+22	1.168E+23	4.032E+23	5.930E+23
Emergy yield (sej)	$Y=R+N+F+G+P_2I$	5.207E+23	6.059E+23	6.491E+23	6.453E+23	1.236E+24	1.630E+24
Emergy used from home sources	$(N_0+N_1+R)/U$	91.93%	94.16%	95.02%	86.43%	84.79%	86.33%
Ratio of export to imports	$(B+P_1E+N_2)/(F+G+PI)$	1.36	2.08	3.09	1. 47	2.73	3.46
Percent renewable	R/U	55.41%	58.51%	51.31%	43.44%	26.97%	21.43%
EDR	U/GDP	1.96E+14	1.49E+14	5.73E+13	3.15E+13	2.01E+13	1.52E+13
ELR	$(N+F+G+P_2I)/R$	0.87	0.80	1.13	1.54	3.72	5.06
Emergy density (sej/m^{-2})	U/Area	4.24E+11	4.85E+11	5.01E+11	4.95E+11	8.21E+11	1.06E+12
Use per person (sej capita^{-1})	U/Population	2.43E+16	2.65E+16	2.60E+16	2.47E+16	4.07E+16	5.22E+16
EYR	$Y/(F+G+P_2I)$	12.86	18.06	21.00	8.13	8.37	9.50
EmSI	EYR/ELR	14.72	22.47	19.41	5.28	2.25	1.88

each element being given by the lengths of the perpendiculars from the given point to the side of the triangle opposite to the appropriate element. Consequently, the "composition" of any point on a ternary diagram can be determined by reading from zero along the basal axis at the bottom of the diagram to 100% at the vertex of the triangle. Simplification of R/Y, N/Y, F’/Y, Y, EYR, ELR, and EmSI are respectively R, N, F’, 1, 1/F’, (1–R)/R, and R/[(1–R)F’]. The sustainability lines depart from the N apex in the direction of the RF’ side and allow the division of the triangle into sustainability areas, which are useful for identifying the sustainability and its development of the system (Almeida *et al.*, 2007). EmSIs ranging from 1 to 10 indicate a system that is sustainable and vigorous, values less than one are indicative of consumer-oriented economies, and values greater than ten suggest an undeveloped economy (Brown and Ulgiati, 1997).

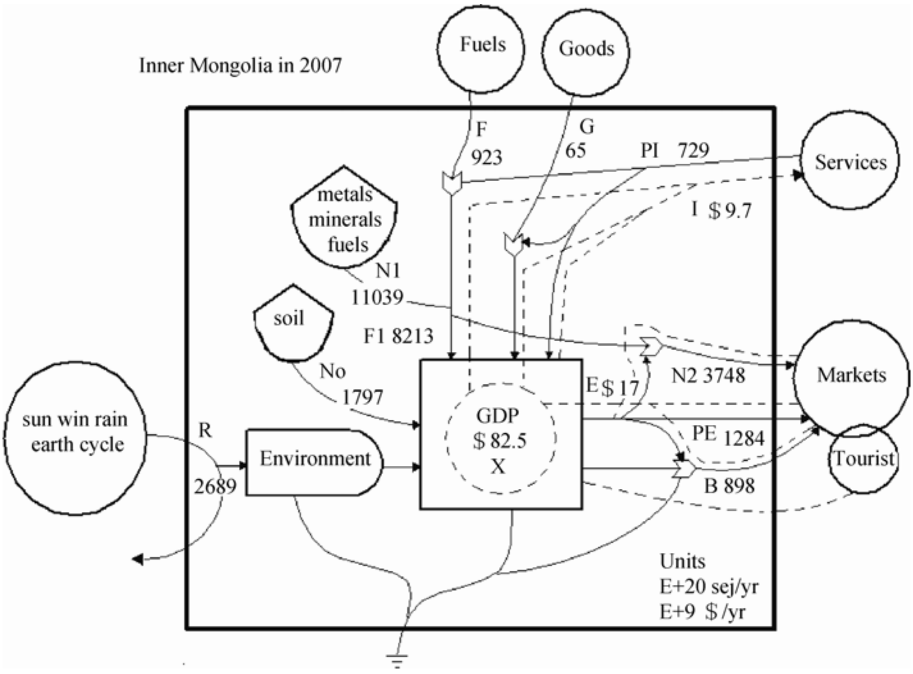

Figure 2 Aggregated diagram of IMAR’s economy in 2007 and emergy resource base used for the calculation of indices (see Table 1). Symbols: R: Renewable sources; N_0: Dispersed non-renewable sources; N_1: Concentrated non-renewable resources; F: Imported Fuels; G: Imported goods; P_2I: Imported Services; I: Dollars paid for all imports; N_2: Exported without full use; B: Exported products; PE: Total exported services; E: Dollars paid for all exports; X: Gross region product. Emergy flows times E+20 sej yr^{-1}; dollar flows times E+9 \$ yr^{-1}.

Data used in this study are from the public information produced by different administrative divisions of IMAR. Detailed information on local resource production and consumption as well as imports and exports are from the Inner Mongolia Statistical Yearbook (IMSY, 1988–2008); data on IMAR’s energy production, consumption, and circulation are from the China Energy Yearbook (CEY, 1998–2008) and China Statistical Yearbook (CSY, 2000–2004); data on IMAR’s iron ore production and circulation come from the China Steel Yearbook (CSY, 2008).

3 Results and discussion

3.1 Emergy flows in IMAR

Total emergy use increased from 5.02×10^{23} sej in 1987 to 1.255×10^{24} sej in 2007, of which >84% was derived from within IMAR. Imported emergy flows (F’, 4.9%–17.1%) are small compared to local flows ($R+N_0+N_1$, 82.9%–95.1%), reflecting a high potential for self-sufficiency and economic security (Figures 3 and 4). Before 2003, local renewable resources (R) amounted to >40% of the total emergy use, while this fraction dropped sharply afterward due to the accelerated consumption of local non-renewable resources and imported emergy, representing an increasingly unsustainable system. For example, the percentage of local non-renewable emergy (N_0+N_1) increased from 36.5% in 1987 to 64.9% in 2007 and the percentage of imported emergy increased from 8.0% to 13.6%. The concentrated use of local non-renewable emergy (N_1) accounts for the largest share after 2004 and reached 58% in 2007.

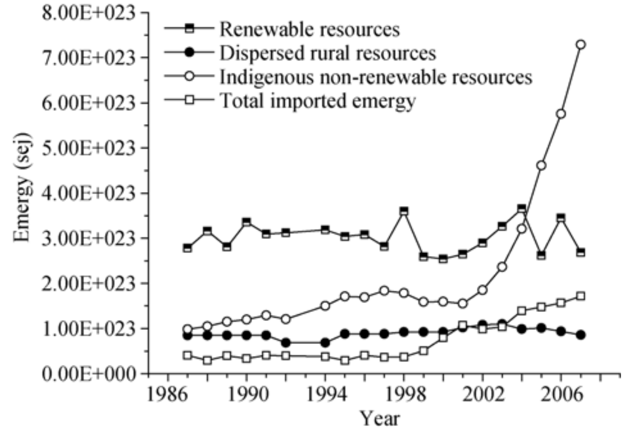

Figure 3 Changes in components of total emergy use (i.e., $R+F+G+P_2I+N_0+N_1$) in IMAR (1987–2007)

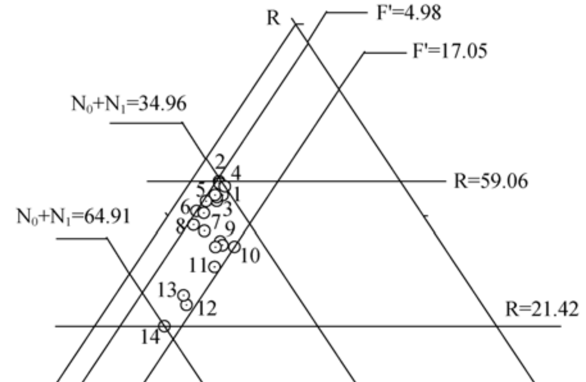

Figure 4 Ternary diagram representing IMAR's resource structure (1987–2007), where $U=(R+N_0+N_1+F)=1$, R, (N_0+N_1) and F' are simplification of R/U (fraction of renewable resources to total emergy use), (N_0+N_1)/U (fraction of indigenous non-renewable resources to total emergy use), F'/U (fraction of imported emergy to total emergy use) respectively. Years: (1) 1987, (2) 1988, (3) 1989, (4) 1992, (5) 1994, (6) 1995, (7) 1996, (8) 1997, (9) 2000, (10) 2001, (11) 2004, (12) 2005, (13) 2006, and (14) 2007.

3.1.1 Renewable resources and production

The renewable resources of IMAR remained fairly constant and fluctuated around 3.0×10^{23} sej yr^{-1} from 1987 to 2007, but decreased its fraction in total emergy use from 55.41% to 21.42%. Of all of the renewable resource inputs, only the largest item – the geo-potential energy of rain and the earth-cycle energy – is taken into account to avoid double accounting. The largest renewable production in IMAR is from agriculture, followed by livestock production and timber production. Livestock and agricultural production increased from 5.36×10^{22} sej and 1.29×10^{22} sej in 1987, respectively, to 1.35×10^{23} sej and 9.93×10^{22} sej in 2007, when they respectively accounted for 56% and 41% of total renewable resource production. The ratio of local renewable production to renewable resources increased continuously from 0.26 in 1987 to 0.90 in 2007, indicating that there is a large development of agriculture and husbandry in IMAR that emergy from renewable resources is transformed into renewable production. The area of grassland of IMAR has increased from 383,102 km^2 to 57,4441 km^2 during 1993–2007 and cropland increased from 84,845 km^2 in 1993 to 140,283 km^2 in 2003 and than decreased to 10,1981 km^2 in 2007 (John *et al.*, 2008). The above results, which are based on remote sensing technology, matches with the government statistics well and confirm an uprising change in agriculture and husbandry land use in IMAR from 1993 to 2007.

3.1.2 Production and use of non-renewable resources

Local non-renewable resources (N), increased from 2.023×10^{23} sej in 1987 to 1.190×10^{24} sej in 2007, provide IMAR economy with strong driving forces. The largest production of emergy from non-renewable resources in IMAR is from coal production followed by iron ore and calcium carbide production, which increased respectively from 6.72×10^{22} sej, 4.67×10^{22} sej, and 2.6×10^{20} sej in 1987 to 6.99×10^{23} sej, 3.363×10^{23} sej, and 2.61×10^{22} sej in 2007, accounting for 63%, 30%, and 2% of the concentrated non-renewable resource production (N_1+N_2), respectively. Use of fossil fuel energy increased from 6.54×10^{22} sej in 1987 to 4.06×10^{23} sej in 2007, which accounted for 30% of the total emergy use. In 2007, coal production accounted for 90.50 % of the emergy in the energy used in IMAR, followed by natural gas (2.41%), petroleum (1.39%), and hydro-power (0.33%) (IMSY, 1988–2008). The correlation analysis between the emergy of coal production and real GDP of IMAR during 1987–2007 ($R=0.979$, $p<0.01$) demonstrated a strong positive correlation with real GDP, suggesting that the importance of mineral production in promoting IMAR's economic growth.

3.1.3 Imports and exports

Being an important energy-generating region and a major fuel supplier to other regions in China, large amounts of energy resources have been exported to meet China's extremely rapid increasing energy consumption. About 52.9% of the coal mined in IMAR was exported in 2007. There appears to be a large difference between the total exports and the total imports of IMAR. From 1987 to 2007, the total imports increased from 4.048×10^{22} sej to 1.716×10^{23} sej while the exports increased from 5.507×10^{22} sej to 6.122×10^{23} sej. Prior to 2001, the imports and exports of IMAR increased very slowly; however, the growth of exports exceeded that of imports by a large margin after 2001 and resulted in total exports being 4.75×10^{23} sej more than total imports in 2007. This rapid increase was due to the rapid growth of coal and electricity exports after 2001. In 2007, the exports/imports emergy ratio of 3.46 means that IMAR imports a lot less emergy than it exports, indicating a large imbalance in the exchange of real wealth with other Chinese provinces and foreign countries. However, if coal production (3.44×10^{23} sej in 2007) is removed from the import-export balance, the import/export emergy ratio changes greatly, such that emergy imports are actually 2% larger than exports. The imports are primarily for metal ores, fossil fuels, and services, of which coal and petroleum are large shares (accounted for ~34% of the total imports in 2007) with emergy rising from 1.48×10^{22} sej in 1987 to 5.87×10^{22} sej in 2007 and imported services increased from 1.11×10^{22} sej to 7.28×10^{22} sej. The exports also include mainly coal, electricity, and services, with coal ranked first with emergy from 1.91×10^{22} sej in 1987 to 2.53×10^{23} sej in 2007. The consumption of coal accounts for 70% of the total energy consumption of China (Jiang *et al.*, 2010) and there appears no sign of decreasing any time soon.

3.2 Emergy intensities

We used several indices to characterize emergy intensity in the context of economy, population, and over space. The indices of emergy intensities: emergy/dollar ratio, emergy use per person, and empower density are the result of total emergy use (U) divided respectively by GDP, population, and area of the study system.

The emergy/dollar ratio (EDR) of IMAR decreased from 1.96×10^{14} sej $\$^{-1}$ in 1987 to 1.52×10^{13} sej $\$^{-1}$ in 2007, which indicates that the power of a dollar for purchasing real wealth in IMAR is declining while the relatively high absolute values indicate that most resources used in economic activities are extracted from the natural environment. In general, the EDR value in IMAR has always been higher than the average of China (Yang *et al.*, 2010), but the gap was narrowed from 1987 to 2007 (Figure 5). The current difference suggests that IMAR will lose in most trades with regions that have lower emergy/dollar ratios. Exportation of raw materials (e.g., coal, metal ore) showed rapid growth after 2001, suggesting more emergy to the purchasers than their purchase capacity. With increases in trade and exchange, there will be a growing imbalance in energy and resource use between IMAR and its neighboring areas in China. Clearly, before EDR falls to a critical level, the raw materials should be used more to make final products of high merchandising value.

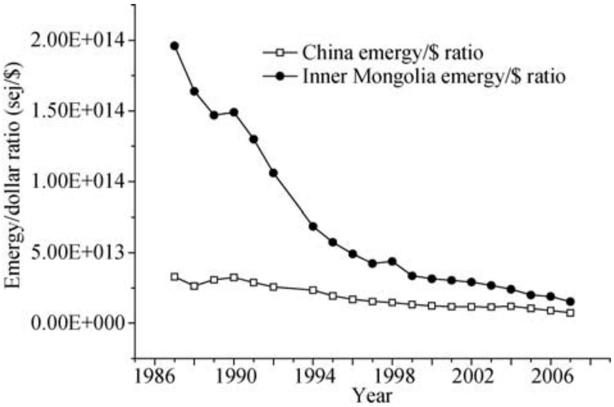

Figure 5 Changes in emergy/dollar ratio for IMAR and China from 1983 to 2007, showing that the EDR of IMAR is approaching the average value for China

The quality of life in IMAR as measured by the emergy use per person (4.07×10^{16} sej capita^{-1} in 2005) is nearly 2.4 times that of the national average (Yang *et al.*, 2010), but many conventional social indicators seemed depressed (CSY, 2008). For example, the indicators of per capita net income and expenditures of urban residents of IMAR (1185.24 and 858.54 US$, respectively) were below the national average (1300.22 and 984.22 US$, respectively). This paradoxical situation can occur if the benefits of high emergy use are not accurately

accurately and completely conveyed to people by the economic system. From 1987 to 2007, the population in IMAR increased from 20.66 million to 24.05 million and the emergy use per person increased from 2.43×10^{16} sej to 5.22×10^{16} sej. After 2000, the annual growth rate of emergy use per person reaches 11.3%. However, IMAR does not maintain a value-added surplus in the products it provides to the nation relative to those that it receives (e.g., the EDR of IMAR is much smaller than the national average level). The high emergy use per person instead comes, in large part, from coal and metal ore mining. Much of the emergy value of these raw materials is not included in the dollar flows that affect the amount of emergy that can be purchased from outside IMAR.

Emergy density of IMAR (8.21×10^{11} sej km^{-2} in 2005) is 2.9 times lower than that of the nation, indicating that IMAR has a less-concentrated emergy use. The emergy density of IMAR increased from 4.24×10^{11} sej m^{-2} in 1987 to 1.06×10^{12} sej/m^{-2} in 2007. Regions with large flows of renewable emergy (e.g., region with large mountains, coastlines, and continental shelf areas) tend to have high emergy density, followed by the industrialized regions, while regions with small flows of renewable and non-renewable emergy use tend to have low emergy density (Brown *et al*., 2009). For IMAR, in 2009, 51.2% of the land area was covered by grassland and 24.5% was barren (John *et al*., 2009), which might be one of the reasons for IMAR's low emergy density.

3.3 Indices of economic efficiency

Emergy yield ratio (EYR, the ratio of the emergy of the output Y divided by the emergy of those purchased from economies outside the system, Odum, 1996) can be used to evaluate the ability of a system to exploit local resources and measure the economic efficiency of the system. During 1987 and 2007, the emergy yield (Y=N+R+F+G+PI) of IMAR fluctuated from 5.2×10^{23} sej to 1.6×10^{24} sej (Table 2) and the EYR varied between 22.0 and 6.5 (Figure 6). The high EYR is largely due to the relatively large amount of renewable resource input, rapid growth of non-renewable resources, and small quantity of emergy transferred into the region from the outside economy. Coal production constitutes a high proportion (>10%) of emergy yield and shows an uprising trend (42.9% in 2007). It is noted that EYR declined sharply from 19.7 in 1998 to 6.5 in 2001. The reason for this change is that there was a very small amount of purchased emergy from economies outside IMAR before 1998 and it in-

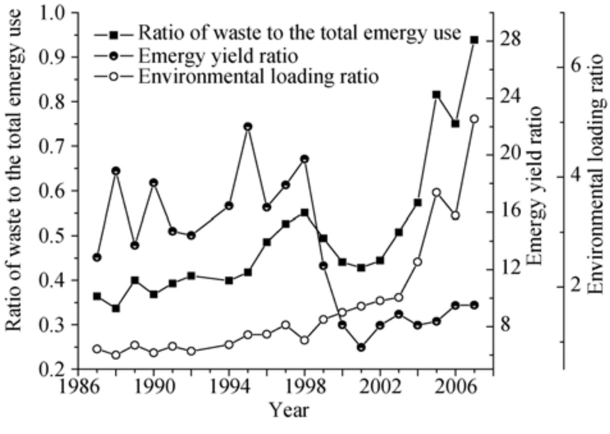

Figure 6 Changes of emergy yield ratio (EYR), waste to total emergy use ratio, and environmental loading ratio (ELR) from 1983 to 2007 in IMAR

creased significantly afterwards, while emergy yield had a decline after 1998. This change of EYR indicated that the economic efficiency of IMAR had a significant decline after 1998 and the purchased emergy did not produce adequate emergy-yield effects relative to the case before 1998. The 1997–1998 El Nino was the strongest in known history, leading to extremes in precipitation in IMAR (426.8 mm in 1998) and reduced the production of mineral resources from 2.43×10^{23} sej in 1998 to 2.20×10^{23} sej in 2000. After 2000, the Western China Development Plan promoted the production of coal and emergy yield greatly, resulting in a growing tendency in EYR.

The emergy exchange ratio (EER), a measure of trade efficiency, is the ratio of emergy received by the buyer to the emergy given in a trade or sales transaction. Emergy gain to the nation from trade with IMAR is evidenced by the EER for coal, petroleum, and steel. Raw products (e.g., minerals, rural products from agriculture, fisheries, forestry) tend to have high EER at market price. This occurs as a result of money being paid for human services but not for the extensive work of nature that went into the original generation of these products. For example, IMAR exported 3.44×10^{23} sej of coal (\$60.9 per ton) in 2007 at a price of \$10.6 billion. The EER for IMAR coal in 2007 can be tallied as: $(3.44\times10^{23}\ \text{sej yr}^{-1})/[(\$1.06\times10^{10}\ \text{yr}^{-1})\ (7.53\times10^{12}\ \text{sej}\ \$^{-1})]$: $(3.44\times10^{23}\ \text{sej yr}^{-1})/(8.0\times10^{22}\ \text{sej yr}^{-1}) = 4.3{:}1$. The net benefit to the buyer of IMAR coal is 4.3 times the buying power of the money paid. From this analysis, one can estimate that the long-term equilibrium price for coal with assumed emergy parity of the exchange and the emergy-to-dollar ratio of the Chinese economy in 2007, which is ~\$261 per ton. For some main export commodities of foreign trade, e.g., steel, rare earth metals, and petroleum, the EER values are 12.93, 2.10, and 6.78, respectively. Obviously, IMAR contributes large fluxes of real wealth to support growth in the regional, national, and global economies.

3.4 Environmental pressure

From a waste production view, environmental pressures of IMAR can be measured by the ratio of emergy in waste produced to the total emergy used, which increased from 0.364 in 1987 to 0.939 in 2007 (Figure 6). The total waste output increased from 1.82×10^{23} sej to 1.18×10^{24} sej. After 2001, both measures increased greatly, indicating that IMAR is farther away from its balanced position as compared to the surrounding provinces. The overall rising trend of these two values was similar to the trend of indigenous non-renewable resources (N1). Such an expected result is alarming for IMAR's fragility in natural resources and an immediate return to its policies to reduce its environmental pollution and dependence on non-renewable resources is needed.

The environmental loading ratio (ELR), the ratio of non-renewable and imported emergy use to renewable emergy use (Odum, 1996) of IMAR increased from 0.87 in 1987 to 5.06 in 2007 (Figure 6), an increase of 4.8 times, which suggests that the pressure of economic activities on local environmental resources had been elevated. The ELR considers environmental pressures from the perspective of the renewable capacity of the environment to support economic processes and human endeavors. A high ELR value indicates rapid economic development and high environmental loads. After 2003, with the accelerated exploitation of non-renewable resources such as coal and metal ore, the ELR increased at an even higher rate. The relatively moderate absolute values of the ELR, however, are likely due to the large land areas in IMAR (i.e., high capacity) that absorb waste, recycle by-products, and provide other environmental services that are of fundamental importance to its sustainability.

3.5 Emergy-based sustainability index (EmSI)

The EmSI evaluates a system's long-term sustainability relative to others, with low EmSI values indicating the systems consuming a relatively large fraction of total emergy in the form of non-renewable emergy and imported emergy (Brown *et al.*, 2009). The ternary diagram of IMAR between 1987 and 2007 is shown in Figure 7. During 1987–1998, EmSI values were higher than 10 and fluctuated between 14 and 25, reflecting underdevelopment of IMAR. The decrease in the EmSI was noticeable from 1998 (19.07) to 2007 (1.88), which indicates rapid economic development and sharply decreasing sustainability. IMAR relies more on non-renewable resources and imports after 1998. From 2000 to 2007, IMAR varied its EmSI values between 1 and 5, suggesting that IMAR is characterized by medium-run sustainability. The average resource line from 1987 to 1998 is F'=0.053, with EYR=18.9, and the average resource line from 2000 to 2007 is F'=0.111, with EYR=9. With the fraction of renewable resources decreasing from 0.497 to 0.156, the ELR value increased nearly four times. A combination of the decrease in the EYR (i.e., increase in F') and increase in ELD (i.e., decrease in R) reduced the EmSI value by ~92% from 1988 to 2007. This declining trend needs to be interpreted in order to enhance the long-run sustainability for IMAR's future.

Here, our concern is about the future sustainability of IMAR. When R is significantly lower than N, EmSI is mainly determined by the value of R/F'. The graphic tool permits the presentation of sensibility lines (e.g., S_N in Figure 7), along which R/F' keeps constant, that one can follow for the variation of N. As line S_N suggests, an increasing N will lead to a simultaneous increase of both EYR and ELR or a decrease of EmSI, which keeps higher R/F' values. For IMAR, R during the study period was always greater than F', with a mean R value that is 4.1 times of F'. After 1998, N and F' began to increase and caused a decrease in R/N to 0.23 and R/F' to 1.56 in 2007, which is close to the EmSI value (1.88). The S_N line seems always above line EmSI=1, which suggests that if the R/F' ratio keeps greater than 1, the EmSI of IMAR will be >R/F' >1, which indicates that IMAR is a sustainable system. However, with continued

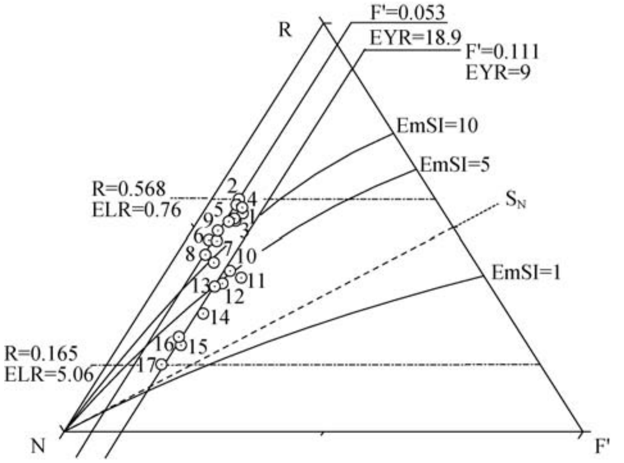

Figure 7 The ternary diagram for IMAR (1987–2007) with sustainability lines (EmSI=1, 5 and 10) and sensitivity lines (S_N), where Y=(R+N+F') =1, R, N and F' are simplifications of R/Y, N/Y and F'/Y, respectively. Years: (1) 1987, (2) 1988, (3) 1989, (4) 1991, (5) 1994, (6) 1995, (7) 1996, (8) 1997, (9) 1998, (10) 2000, (11) 2001, (12) 2002, (13) 2003, (14) 2004, (15) 2005, (16) 2006 and (17) 2007.

actions in the exploitation of non-renewable resources, it is bound to have a shortage of resources. When non-renewable resources are stretched to the limits, IMAR has to increase its imports, which will lead a decrease of the R/F' ratio and EmSI. If using current levels of non-renewable resource production (1.19×10^{24} sej in 2007) as a benchmark and the average value of R (3.021×10^{23} sej) and the average annual increment of imported emergy from 1998 to 2007 (1.45×10^{22} sej), it will take 9 years for the R/F' ratio to decrease to <1 and 13 years for the EmSI value to decrease to <1 when IMAR turns into an unsustainable system.

4 Conclusions and policy implications

More than 83% of the total emergy use in IMAR was derived from its sources from 1987 to 2007, indicating a strong capacity for self-sufficiency. The total renewable resources of IMAR fluctuate around 3.0×10^{23} sej in corresponding to a decreased fraction of total emergy use from 55.41% to 21.42% over the study period. Local non-renewable resources (N) increased from 2.023×10^{23} sej in 1987 to 1.190×10^{24} sej in 2007, providing the IMAR economy with most of its driving forces. From 1987 to 2007, the total imports increased from 4.048×10^{22} sej to 1.716×10^{23} sej while the exports increased from 5.507×10^{22} sej to 6.122×10^{23} sej. The rising exports/imports emergy ratio from 1.36 to 3.46 and rising EDR from 1.96×10^{14} sej $\$^{-1}$ to 1.52×10^{13} sej $\$^{-1}$ indicate a large imbalance in the exchange of real wealth of IMAR with other Chinese provinces and/or with foreign countries (i.e., Japan, Europe, and the Americas). The emergy used per person increased from 2.43×10^{16} sej to 5.22×10^{16} sej, suggesting that IMAR's overall standard of living has been lifted significantly. The emergy density of the IMAR increased from 4.24×10^{11} sej m^{-2} in 1987 to 1.06×10^{12} sej m^{-2} in 2007. The ratio of waste to total emergy use increased from 0.364 to 0.939 and the environmental loading ratio rose from 0.87 to 5.06, which suggests that the pressure of economic activities on local environmental resources grew quickly. The EmSI decreased from 14.72 to 1.88, suggesting that IMAR has been turned into a system where sustainability is in its medium temporal term.

Changes in the development of IMAR and China seemed similar. We suspect that the overall economic development process in China and the Western China Development Plan are the two primary drivers for IMAR. According to Yang (2010), China stepped into a stage of rapid growth in all aspects of the economy after 2000, such that the concentrated emergy use increased 55.2% from 2000 to 2005 and the ratio of emergy use per person and per unit area showed a trend of rapid increase. Here, we found that 2001 appears to be the turning point for a number of relevant metrics. Prior to 2001, most emergy flows, ratios, and indices were slowly changing but turned to fast motion afterward. From 2001 to 2007, the total emergy use increased by 99%, local non-renewable resources increased by 2.61 times, and total imports increased by 60%. Meanwhile, the total exports increased by 4.65 times and were accompanied by the ELR increasing by 1.79 times. The ratio of waste to total emergy use increased by 1.29 times and the EmSI decreased by 53%.

Clearly, indigenous resources need to be processed in IMAR before exportation. Lowering the EER of exported commodities by decreasing the proportion of direct environmental resource inputs, which is unpaid, should be seriously considered and implemented. After processing, the price of resources will have "added value" that will eliminate the emergy advantage to buyers by reducing the EER of non-renewable resources to 1 (i.e., the balanced condition). Importing goods and fuels from other regions that have higher EDR rates would be among other management options for IMAR. In sum, one can only control the amount of N and F’ to adjust the proportions of resources in an appropriate range because the amount of R supporting an economy is a constant function of the region’s geography. For IMAR, reducing the exploitation of non-renewable resources is important because the proportion of imports in total emergy use is not large. To maintain the R/F’ ratio >1, it is essential to introduce advanced technology, sound management plans, and adaptive policies to enhance the rates of resource exploitation and utilization efficiency as well as import more goods and resources with EER values of >1 to reduce the dependence on local non-renewable resources.

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