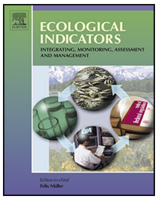
Ecological Indicators 74 (2017) 198–204

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



The emergy of metabolism in different ecosystems under the same environmental conditions in the agro-pastoral ecotone of northern China

Xiajie Zhai[a,b], Ding Huang[a,b], Shiming Tang[a], Shuiyan Li[a], Jianxin Guo[a], Yuejuan Yang[a], Hongfei Liu[a], Jinsheng Li[a], Kun Wang[a,b,*]

[a] *Institute of Grassland Science, China Agricultural University, Beijing 100093, China*
[b] *GuYuan National Grassland Ecosystem Field Station, Hebei Province 076550, China*

ARTICLE INFO

Article history:
Received 2 June 2016
Received in revised form
16 November 2016
Accepted 17 November 2016

Keywords:
Agro-pastoral ecotone
Emergy evaluation
Ecosystem
Grassland
Farmland

ABSTRACT

The sustainability of ecosystem productivity and rules governing ecosystem development are important topics of scientific research. The emergy approach is an effective method for investigating these topics, especially when used to evaluate systems that have developed under the same environmental conditions, such as climate and soil. In this paper, emergy differences between terrestrial ecosystems were studied in Guyuan County, a region representative of the agro-pastoral ecotone in Hebei Province, China. A combination of field tests and a questionnaire survey were carried out between June and August 2015. The ecosystems studied included natural grassland, artificial grassland, field crops and commercial crops. These four ecosystems were further subdivided into a total of ten ecosystems. Natural grassland was divided into free-grazing and mowed ecosystems; artificial grassland consisted of oat, Chinese leymus and corn silage; field crops included naked oats, flax and wheat; and commercial crops consisted of cabbage and potatoes. The results showed that the rain input of 4.78×10^{14} seJ/ha/yr constituted the highest renewable natural resource emergy and that the purchased emergy inputs of the ten ecosystems ranged from 3.53 to 147.67×10^{14} seJ/ha/yr. Natural resource emergy input was the basic power to maintain the ecosystem, and purchased emergy input was the direct cause of the development of the ecosystems. Groundwater was the most important non-renewable purchased energy for the production of economic crops. The emergy investment ratios (EIR) for potatoes (27.81) and cabbage (19.03) were higher than those of the other ecosystems, but mowed and artificial Chinese leymus grassland had the higher emergy self-sufficiency rates (ESR). Natural grassland, artificial Chinese leymus grassland and traditional grain crops had a low environmental load and high sustainability, whereas potatoes and cabbage had a high environmental load and low sustainability. Overall, rain-fed artificial grassland has a high development potential from the perspective of environment and productivity.

1. Introduction

The sustainability of social-ecological systems is an important topic of scientific research (Krausmann et al., 2013; Liu et al., 2015). Land-use/land-cover change (LUCC) is the most direct manifestation of the effects of human activity on Earth's natural ecosystems and serves as a link between human social and economic activities and natural ecological processes (Mooney et al., 2013). The agro-pastoral ecotone in northern China has gradually become fragmented into a variety of ecosystems in an interlocked mosaic pattern in the interface area between nomadic and agrarian cultures (Zhang et al., 2007). LUCC research focuses on the monitoring and simulation of the dynamic land-use change process along with the coupling of human and environmental systems, material cycles, biosphere-atmosphere interactions, surface radioactive forcing and the sustainable utilization of environmental resources (Rindfuss et al., 2004; Meyfroidt et al., 2013; Mooney et al., 2013). The rapid development of the Chinese economy and population growth have been closely associated with excessive consumption of natural resources and severe land deterioration (Brouwer, 2004; Ji and Chen, 2006; Chen and Chen, 2007; Feng et al., 2009). Therefore, the sustainable utilization of environmental or ecological resources for

---

* Corresponding author at: Institute of Grassland Science, China Agricultural University, Beijing 100093, China.
E-mail address: wangkun@cau.edu.cn (K. Wang).

http://dx.doi.org/10.1016/j.ecolind.2016.11.028

agriculture and animal husbandry in China has been a major challenge. Traditionally, agricultural and pastoral research has focused on increasing yields and enhancing the economic efficiency of different production systems (Rydberg and Haden, 2006; Kemp et al., 2013). However, the ecological costs have not been considered sufficiently, thus leading to severe ecological deterioration in the agro-pastoral ecotone in northern China (Zhang et al., 2007). Hence, there is a need for more integrated accounting procedures that consider both the economic and ecological costs when evaluating production systems to provide a balanced view of comparative resource use. Emergy synthesis is an accounting tool that considers both the environmental and economic inputs that are directly or indirectly required by a process to generate a product and it measures real wealth, independent of financial considerations (Odum, 1988; Brown and Ulgiati, 2004; Ulgiati et al., 2007; Ghaley and Porter, 2013; Zhang et al., 2016). The Chinese Academy of Sciences and the Natural Science Foundation of China, the U.S. Environmental Protection Agency, the EU, and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development are pursuing projects to evaluate the assessment capability of emergy (Geng et al., 2013). Many studies have conducted emergy analyses of large regions such as nations (Ulgiati et al., 1994; Wright and Østergård, 2016; Zhang et al., 2016), cities (Zhang et al., 2011), counties (Ma et al., 2014), forests (Li et al., 2014), grassland (Dong et al., 2012, 2014) and crop production systems (Martin et al., 2006; Ghaley and Porter, 2013; Patrizia et al., 2014; Zhang et al., 2016). Databases at all levels are necessary to help emergy become a practical policy-making instrument for sustainable or circular development (Geng et al., 2013). Because previous studies were mainly performed at large spatial scales, there is a lack of experimental research at small spatial scales. Additionally, most studies focused on the development of plant communities (Soliveres et al., 2015), make little use of databases or focus on the emergence of mechanisms and rules governing ecosystem development under the same environmental conditions, such as climate and soil. The aim of this paper is to analyze the emergy differences among systems, find consistencies in input and output between different ecosystems operating under the same environmental conditions, evaluate the sustainability of these ecosystems and present data support for research on ecosystem development and government policy decisions in the agro-pastoral ecotone in China.

2. Materials and methods

2.1. Study site

The research was conducted at the National Field Station for Grassland Ecosystems in Guyuan County (latitude 41°46′N, longitude 115°40′E, elevation 1430 m), Hebei Province, China (Fig. 1). The area has a semi-arid continental monsoon climate with a frost-free period of 80–110 days. The annual (1982–2009) mean precipitation is approximately 430 mm (ranging from 350 to 450 mm), and approximately 80% of the precipitation is concentrated in the growing season between June and September. The annual mean air temperature is 1.4 °C. The minimum monthly mean air temperature is −18.6 °C in January, and the maximum is 21.1 °C in July. *Leymus chinensis* is the dominant species of this grassland, and the soil is Calcic-orthic Aridisol (Wang et al., 2015; Chen et al., 2015). Crops mainly consist of naked oats, flax, wheat and corn silage.

2.2. Experimental design and treatments

Four land-use types, including natural grassland, artificial grassland, field crops and commercial crops, were selected for the study. The natural grassland was divided into free-grazing and mowed grassland ecosystems; the artificial grassland was comprised of three ecosystems: oats, Chinese leymus and corn silage; field crops included naked oats, flax and wheat; the commercial crops considered were cabbage and potatoes; thus, there were ten ecosystems in total. All of the ecosystems have been in stable use for over 5 years.

Field sampling was carried out in August 2015. Aboveground biomass and underground biomass (0–30 cm) were measured using the harvest method. The dry weight of biomass was measured after drying at a temperature of 65 °C for 48 h. Cabbage, potatoes and corn silage were cut into several pieces for drying. From June to July 2015, status questionnaires were given to 5 households for each ecosystem. The questionnaire consisted mainly of questions concerning basic farming metrics such as yield, area, and population; material inputs such as seeds, manure, labor, diesel, iron fencing, electrical power, ground water, nitrogen, phosphorus, potassium, compound fertilizer, pesticides, agricultural films; and economic outputs such as gross income, cost and net income.

2.3. Data statistics and analysis

In emergy synthesis, the system boundary is defined to assess the inputs and outputs of the system studied (Fig. 2). The inputs and outputs crossing the boundary of analysis were inventoried. Local renewable inputs consisted of sun, wind, rain, seeds, manure and labor, and local non-renewable inputs consisted of topsoil loss, groundwater, diesel, iron, electricity, fertilizer, pesticide and agricultural films (Table 1 and 2). Labor input consisted of the various costs incurred between land preparation and harvest. The units given in joules and grams were then multiplied by solar transformity coefficients to convert to units of solar emjoules (seJ). The value of emergy can be obtained using the following equation: Emergy = available energy of an item × transformity (Odum, 1988; Campbell, 2001; Dong et al., 2012). Conversion of the different flows into emergy was done with reference to the geobiosphere emergy baseline of 12E + 24 seJ/year in the latest work (Brown et al., 2016; Campbell, 2016); therefore, we transformed data from other studies to our chosen baseline. For example, data which were relative to the 9.26E + 24 and 15.83E + 24 seJ/year baseline were converted to the 12E + 24 seJ/year by multiplying by a conversion factor of 1.3 and 0.758.

3. Results

3.1. Emergy flows including input, composition and output

Natural resource inputs included local renewable (R) and local non-renewable (N) inputs. Because the sun, wind and rain were co-products of coupled processes, the chemical potential energy input of rain (4.78×10^{14} seJ/ha/yr, Table 1), which constituted the highest emergy flow of the three, was considered to be the entire renewable resource emergy flow to avoid overestimating renewable inputs; the renewable resource emergy flow was considered to be the same for each ecosystem in the study area.

The main categories of purchased emergy and emergy flows into all of the ecosystems are summarized in Tables 2 and 3. Table 3 lists the purchased emergy inputs for each ecosystem and categorizes them as renewable organic emergy (O) or non-renewable industrial purchased emergy (P). Renewable organic emergy includes seeds, manure and labor; non-renewable industrial purchased emergy includes diesel, iron fencing, electrical power, ground water, nitrogen, potassium, compound fertilizer, pesticides and agricultural films. For comparison, all flows were expressed in units of annual solar emergy (seJ) per hectare. There was a significant variance in

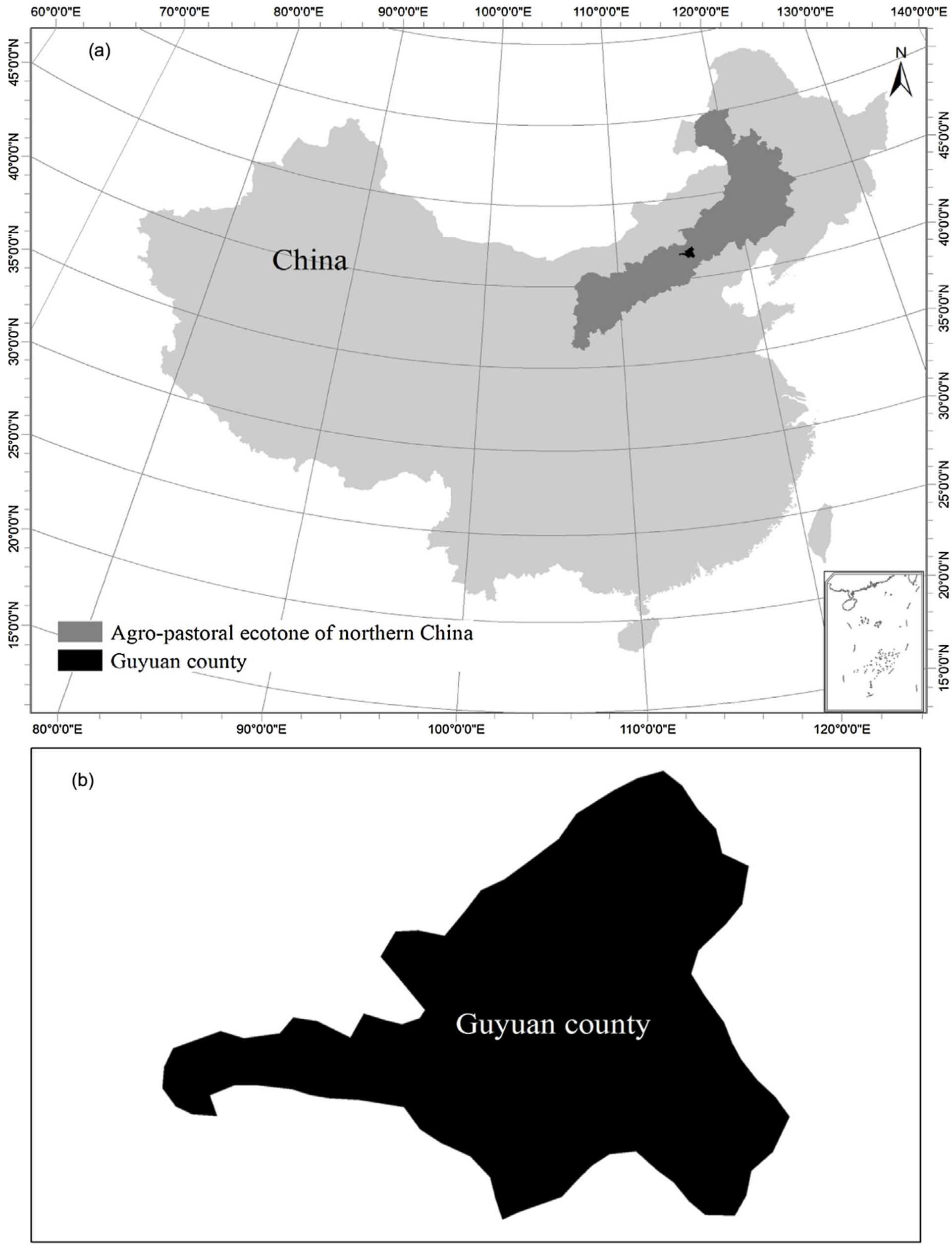


Fig. 1. Site maps: (a) the location of agro-pastoral ecotone of northern China (according to Zhao et al., 2002); (b) outlines of Guyuan county, a typical representative county of the agro-pastoral ecotone.

total emergy input, ranging from 3.53×10^{14} seJ/ha/yr in mowed grassland to 147.67×10^{14} seJ/ha/yr in potatoes. The value of purchased emergy inputs to potatoes and cabbage is higher than 100, corn silage and oats are higher than 10, and the others are less than 10. The sum of O ranged from 2.57×10^{14} seJ/ha for mowed grassland to 51.49×10^{14} seJ/ha for potatoes; the sum of I ranged from 0.09×10^{14} seJ/ha for free-grazing grassland to 96.19×10^{14} seJ/ha for potatoes.

Among the various purchased inputs for different ecosystems, groundwater, labor and electrical power consumed the bulk of the emergy (Table 3). Diesel and fertilizer consumption had the second highest emergy inputs, and the emergy consumption for other field operations was low or negligible. In potatoes and oats, groundwater emergy input (per ha) was the highest, constituting 44.66%, and 42.25% of the total purchased emergy input, respectively, followed by the emergy input for labor (34.85% and 32.92%, respectively) and electric power (13.75% and 12.99%, respectively). The proportion of labor and groundwater were 50.93% and 39.16% for cabbage. The area planted in potatoes and vegetables was (3.33×10^4 ha) and showed and an increasing trend year by year. This area accounted for 9.12% of the county's area (3.65×10^5 ha). The use of groundwater is a concern and should be studied. In general, labor, groundwater, electricity and diesel fuel constituted >97% of the purchased emergy in put to all ecosystems.

The energy output for all of the ecosystems was calculated based on the dry matter of grain or straw (Table 4). The energy output ranged from 9.36×10^9 J/ha in free grazed grassland to 182.81×10^9 J/ha in potatoes. The grain energy of potatoes, naked oats, wheat, and flax was used to analyze the solar transformity, the other ecosystems were the straw energy. Cabbage had the greatest solar transformity of 6.34×10^5 seJ/J, followed by free

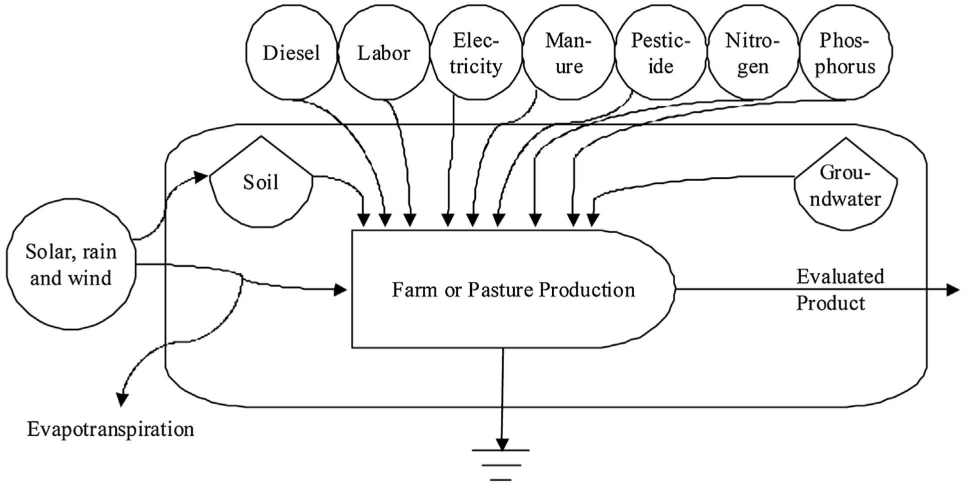


Fig. 2. A general energy flow diagram of the agricultural production system.

⟶ Energy circuit. A pathway whose flow is proportional to the storage. ○ Constant force source. ⬠ Storage. ◗ Producer. ⏚ Heat sink. ▭ System frame.

Table 1
Emergy inputs of local natural resources in Guyuan county, China.

Inputs	Raw data (J/ha/yr)	Solar transformity (seJ/J)[a]	Emergy (seJ/ha/yr)
Local renewable (R)			
Solar energy[b]	5.83×10^{13}	1	5.83×10^{13}
Wind energy[b]	1.52×10^{11}	1911	2.91×10^{14}
Rain chemical potential energy	2.03×10^{10}	23,530	4.78×10^{14}
Chemical potential energy of evapotranspiration[b]	8.04×10^{10}	36,530	2.94×10^{15}
Local non-renewable (N)			
Net topsoil loss (organic matter)	5.61×10^{8}	94,380	0.53×10^{14}
Sum of natural inputs			5.31×10^{14}

Solar energy = 10,000m^2 (area) × 5.83×10^9J/yr (annual average solar radiation) = 5.83×10^{13} (J/ha/yr).

Wind energy (Campbell and Ohrt, 2009) = 1.3 kg/m^3 (density) × 1×10^{-3} (drag coefficient) × 7.18 m/s (geostrophic wind velocity)^3 × 10000 m^2(area) × 3.16×10^7 (sec/year) = 1.52×10^{11} (J/ha/yr).

Chemical potential energy of rain (J) = 10000m^2 (area) × 430 mm (rainfall) × 1000 kg/m^3 (rain density) × 4.73J/g (Gibbs Free Energy) (Campbell and Ohrt, 2009) = 2.03×10^{10} (J/ha/yr). Gibbs Free Energy water relative to seawater based on the average temperature (15.12 °C) of the growing season in Guyuan County.

Chemical potential energy in evapotranspiration (J) = 10,000m^2 (area) × 1.7 m (annual average evapotranspiration) × 1000 kg/m^3 (density) × 4.73J/g (Gibbs Free Energy) (Campbell and Ohrt, 2009) = 8.04×10^{10} (J/ha/yr).

Net topsoil loss (organic matter) energy (J) = 1.24×10^6 g/ha/yr (average soil erosion) (Zheng et al., 2009) × 0.02 (fraction of organic matter) × (5.4 kcal/g) × (4186J/kcal) = 5.61×10^8 (J/ha/yr).

[a] The baseline of transformities is 12E + 24 seJ/year (Brown et al., 2016; Campbell, 2016), and transformed from (Campbell and Ohrt, 2009).

[b] Values not considered to avoid double counting.

grazed grassland (1.02×10^5 seJ/J), the other ecosystems ranged from 0.16×10^5 seJ/J (corn silage) – 0.84×10^5 seJ/J (potatoes).

3.2. Emergy-based indicators

Table 5 shows the emergy-based indicators for the ten ecosystems in the study area. The emergy investment ratios (EIR) for potatoes (27.81) and cabbage (19.03) were higher than those of the other ecosystems. The emergy self-sufficiency rates (ESR) for mowed and artificial Chinese leymus grassland were the highest, both at 60%, followed by free grazing grassland (55.79%), wheat (43.51%), flax (43.51%), naked oats (43.34%) and corn silage (30.52%), the lowest ESRs were 25.36%, 4.99% and 3.47% for oats, cabbage and potatoes, respectively.

The emergy yield ratios (EYR) for cabbage and potatoes were lower than those for other ecosystems, which had values higher than 1.34. In contrast, the environmental loading ratios (ELRs) for potatoes and cabbage were 31.00 and 21.25 respectively, which were significantly higher than those for other ecosystems; free-grazing, mowed and artificial Chinese leymus grassland had lower ELRs that were close to 0.9. As a result, the emergy sustainability index (ESI), which is the ratio of EYR to ELR, was highest for the group: artificial Chinese leymus, mowed and free grazed grassland; these ecosystems demonstrated higher sustainability because their environmental load was lower and their emergy yield was higher that the other systems examined.

4. Discussion

Immigration and the increase in livestock breeding by herders and crop planting by farmers to improve their livelihoods and keep pace with human population growth have caused land to become gradually fragmentized and have created an interlocked mosaic pattern in the agro-pastoral ecotone in northern China (Zhang et al., 2007; Dong et al., 2012). Furthermore, encouraged by local governments and driven by economic interests, large areas of grassland in northern China were reclaimed, particularly during the last two decades (Liu et al., 2014). Over time, the formation and development of ecosystem diversity in a small region, as mentioned above, included natural grassland, artificial grassland and farmland. Sound or sustainable ecosystem management requires the understanding and proper evaluation of the environmental contributions of an ecosystem that traditional economic evaluations tend to overlook or underestimate; emergy analysis can solve this problem (Campbell, 2001).

Table 2
Energy and other input data of purchased energy to ten ecosystems.

Input category		Potatoes	Cabbage	Corn silage	Chinese leymus	Oats	Naked oats	Wheat	Flax	Mowed grassland	Free grazing
Renewable organic energy	Seeds(kg/ha)	2550	2.25	150	300	150	225	225	75	0	0
	Manure(kg/ha)	0	0	1500	1500	10000	1500	3000	1500	0	0
	Labor($/ha)	1153.85	1153.85	230.76	57.69	115.38	115.38	115.38	115.38	57.69	92.31
Non renewable industrial purchased energy	Diesel(J/ha)	11.73×10^9	11.73×10^9	2.07×10^9	1.03×10^9	2.07×10^9	2.07×10^9	2.07×10^9	2.07×10^9	1.03×10^9	0
	Iron fence(kg/ha)	0	0	0	1000	1000	0	0	0	1000	1000
	Electric power (J/ha)	10.8×10^9	0	0	0	1.08×10^9	0	0	0	0	0
	Ground water(J/ha)	37.05×10^9	22.23×10^9	0	0	3.71×10^9	0	0	0	0	0
	Nitrogen(kg/ha)	0	375	150	0	0	150	0	0	0	0
	Potassium(kg/ha)	750	0	0	0	0	0	0	0	0	0
	Compound fertilizer (kg/ha)	1575	750	150	0	0	150	0	150	0	0
	Pesticide (kg/ha)	10	10	0.5	0	0	0.5	1	0.5	0	0
	Agricultural films(kg/ha)	45	45	0	0	0	0	0	0	0	0

Table 3
Emergy inputs of purchased emergy to ten ecosystems.

Input category	Inputs	Solar transformity (seJ/unit)	Emergy (10^{14} seJ/ha)									
			Potatoes	Cabbage	Corn silage	Chinese leymus	Oats	Naked oats	Wheat	Flax	Mowed grassland	Free grazing
Renewable organic energy (O)	Seeds(g)	9.1×10^8	0.0232	0.0000	0.0014	0.0027	0.0014	0.002	0.002	0.0007	0.0000	0.0000
	Manure(g)	1.62×10^8	0.0000	0.0000	0.0024	0.0024	0.0162	0.0024	0.0049	0.0024	0.0000	0.0000
	Labor($)	4.46×10^{12}	51.4617	51.4617	10.2919	2.573	5.1459	5.1459	5.1459	5.1459	2.5730	4.1170
Sum of O			51.4849	51.4617	10.2957	2.5781	5.1635	5.1504	5.1529	5.1491	2.5730	4.1170
Non renewable industrial purchased energy (P)	Diesel(J)	8.41×10^4	9.8649	9.8649	1.7409	0.8662	1.7409	1.7409	1.7409	1.7409	0.8662	0.0000
	Iron fence(g)	9.1×10^9	0.0000	0.0000	0.0000	0.0910	0.0910	0.0000	0.0000	0.0000	0.0910	0.0910
	Electric power(J)	1.88×10^5	20.3040	0.0000	0.0000	0.0000	2.0304	0.0000	0.0000	0.0000	0.0000	0.0000
	Ground water(J)	1.78×10^5	65.9490	39.5694	0.0000	0.0000	6.6038	0.0000	0.0000	0.0000	0.0000	0.0000
	Nitrogen(g)	3.07×10^{10}	0.0000	0.1151	0.0461	0.0000	0.0000	0.0461	0.0000	0.0000	0.0000	0.0000
	Potassium(g)	1.4×10^9	0.0105	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Compound fertilizer(g)	3.56×10^9	0.0561	0.0267	0.0053	0.0000	0.0000	0.0053	0.0000	0.0053	0.0000	0.0000
	Pesticide(g)	1.91×10^{10}	0.0019	0.0019	0.0001	0.0000	0.0000	0.0001	0.0002	0.0001	0.0000	0.0000
	Agricultural films(g)	4.83×10^8	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sum of P			96.1866	49.5783	1.7924	0.9572	10.4661	1.7924	1.7411	1.7463	0.9572	0.0910
Total (F)			147.6715	101.04	12.0880	3.5354	15.6296	6.9428	6.8939	6.8954	3.5302	4.208

Note: The baseline of transformities is 12E + 24 seJ year^{-1} (Brown et al., 2016; Campbell, 2016). Transformity were gleaned from different sources: seeds (Coppola et al., 2009); manure (Bastianoni et al., 2001); labor(Bo and Ulgiati, 2013); diesel, nitrogen, potassium (Brandt-Williams, 2002); iron fence, electric power, pesticide(Dong et al., 2014); ground water (Buenfil, 2001); compound fertilizer, agricultural films (Lan et al., 2002)

Table 4
Energy outputs and solar transformity of ten ecosystems.

Ecosystems	Output straw or grain energy ($\times 10^9$ J/ha)	Total emergy (R + N + F) ($\times 10^{14}$ seJ/ha)	Solar transformity ($\times 10^5$ seJ/J)
Potatoes	182.81	152.98	0.84
Cabbage	16.78	106.35	6.34
Corn silage	109.17	17.40	0.16
Chinese leymus	37.25	8.85	0.24
Oats	75.23	20.94	0.28
Naked oats	30.38	12.25	0.40
Wheat	36.45	12.20	0.33
Flax	25.05	12.21	0.49
Mowed grassland	11.90	8.84	0.74
Free grazing	9.36	9.52	1.02

Note: The grain energy of potatoes, naked oats, wheat, and flax was used to analyze the solar transformity, other ecosystems were the straw energy.

Table 5
Comparative of emergy indices for ten ecosystems.

Ecosystem types	Ecosystems	Emergy investment ratio(EIR)	Emergy self-sufficiency ratio(ESR)	Emergy yield ratio(EYR)	Environmental loading ratio (ELR)	Emergy sustainability index(ESI)
Parameters		F/(R + N)	(R + N)/(R + N + F)	(R + N + F)/F	(N + F)/R	EYR/ELR
Commercial crop	Potatoes	27.81	3.47%	1.04	31.00	0.0334
	Cabbage	19.03	4.99%	1.05	21.25	0.0495
Artificial grassland	Corn silage	2.28	30.52%	1.44	2.64	0.5452
	Chinese leymus	0.67	60.03%	2.50	0.85	2.9418
	Oats	2.94	25.36%	1.34	3.38	0.3963
Field crop	Naked oats	1.31	43.34%	1.76	1.56	1.1289
	Wheat	1.30	43.51%	1.77	1.55	1.1398
	Flax	1.30	43.51%	1.77	1.55	1.1395
Natural grassland	Mowed grassland	0.66	60.07%	2.50	0.85	2.9481
	Free grazing	0.79	55.79%	2.26	0.99	2.2819

According to the emergy accounting rules, only the larger of the solar and rain emergy can be considered the environmental renewable emergy that drives a natural or semi-natural ecosystem. Similar to Guyuan and Minqin Counties in northern China, where rainfall is relatively lower than in southeast China, rain emergy was always greater than solar emergy when an annual time scale was used (Li et al., 2014). In China, non-renewable inputs such as agricultural mechanical equipment and chemical fertilizer represent the largest contribution to the total input of the crop production system (Zhang et al., 2016). In our opinion, labor and groundwater (especially in arid and semi-arid regions) are also major contributors: in the agro-ecosystem of Luancheng County in North China, groundwater was the greatest contributor to resource inputs (Lu et al., 2010; Ma et al., 2014). The total output of economic crops has far surpassed that of traditional grain crops (Zhang et al., 2016), and the higher prices for economic crops explain why an increasing amount of grassland is being gradually converted to farmland to grow commercial crops. Although economic processes or factors are not within the scope of discussion for this article, it is worth mentioning that economic interest is an important factor in driving these purchased emergy inputs to promote the development of ecosystems.

Emergy indicators (Brown and Ulgiati, 1997) including EIR, EYR, ELR and ESI were estimated as a means of comparing the ecological and economic sustainability of the ecosystems. These indicators have proven useful in the valuation of agricultural or grassland systems (Ghaley and Porter, 2013; Dong et al., 2012; Zhang et al., 2016). The EIR values for potatoes and cabbage were higher than those for other ecosystems, and the value of 7.77 for China's crop production system (Zhang et al., 2016) indicates that more unexploited resources attract investors (Lu et al., 2006). As for the EYR, comparing our results to those of similar research, the average level of agriculture was 1.68 nationally in China (Zhang et al., 2016), 1.03 for wheat production in Denmark (Ghaley and Porter, 2013), 1.07 for corn production in the USA (Martin et al., 2006), and 1.17 nationally in Italy (Patrizia et al., 2014); these results show that the ecosystems in this study except cabbage potatoes,corn silage and oats have a stronger competitive ability. The ELR values for potatoes and cabbage (31.00 and 21.25) were far above the national average (2.10, Zhang et al., 2016), which indicates that the ecosystem is not sustainable, because it relies mainly on non-renewable emergy inputs. The ELR values for free-grazing, mowed and artificial Chinese leymus grassland indicate that these three ecosystems have the lowest environmental load. With the exception of agro-ecosystems that are less environmentally demanding and largely dependent on local renewable resources for production (Ghaley and Porter, 2013), a low ESI (<1) indicates an economy that has been classified as 'developed,' and a high ESI (>10) indicates an economy that has been classified as 'undeveloped.' ESI ratios with values between 1 and 10 are referred to as 'developing economies' (Brown and Ulgiati, 1997). Artificial Chinese leymus, mowed, and free grazed grassland belong to the ESI range of developing economies; cabbage, potatoes and oats belong to the range of highly developed economies with low sustainability; naked oats, flax, and wheat belong to the range of developing economies but are less sustainable than the grasslands. The ESI values of naked oats, wheat and flax were similar, and they were similar compared with the crop production systems in Hebei (1.18), lower than Inner Mongolia (1.46, Tao et al., 2013) and higher than the average level of China (0.80) for the year 2010 (Zhang et al., 2016).

5. Conclusion

The emergy input and output of ten ecosystems demonstrate pronounced differences under the same environmental conditions in one county in the agro-pastoral ecotone in China. This analysis enables us to understand the development of ecosystems under anthropogenic influences. Natural resource emergy input is the basic power to maintain ecosystems; purchased emergy input is the direct cause of the development of the ecosystems under the same environmental conditions. How these ecosystems develop in the future will be the focus of future ecological studies. In addition, groundwater is a major non-renewable natural resource, particularly for commercial crops locally. Natural grassland, artificial Chinese leymus grassland and traditional grain crops have a low environmental load and high sustainability, whereas potatoes and cabbage have the opposite. Corn silage and oats are more sustainable than cabbage and potatoes, but lower than the other field crops, naked oats, wheat and flax. Rain-fed artificial grassland has a high development potential from the perspective of environment and productivity. How to make policy decisions and use rare natural resources impartially, correctly, and in a well-planned manner will be critical issues in the future for protecting the ecological environment and for the safety of food production.

Acknowledgements

This research was supported by the project “The National Scientific Research Institutions to Carry Out An Important Agricultural Extension Service Pilot – Northern Ecology Function Area in Hebei Province” funded by the Ministry of Agriculture and Ministry of Finance, China. The authors are very grateful to local farmers and herdsmen for their patience and support of our work, and we very much appreciate Master Kai Liu and wish to thank him for the help of Fig. 1. We also acknowledge anonymous referees for their careful review and helpful comments on a preliminary version of this paper.

References

Bastianoni, S., Marchettini, N., Panzieri, M., Tiezzi, E., 2001. Sustainability assessment of a farm in the Chianti area (Italy). J. Cleaner Prod. 9, 365–373.

Bo, L., Ulgiati, S., 2013. Identifying the environmental support and constraints to the Chinese economic growth: an application of the emergy accounting method. Energy Policy 55, 217–233.

Brandt-Williams, S.L., 2002. Folio 4: emergy of florida agriculture (2nd printing). In: Handbook of Emergy Evaluation. Center for Environmental Policy. University of Florida, Gainesville, FL, USA.

Brouwer, F., 2004. Sustaining Agriculture and the Rural Environment. Edward Elgar Publishing Ltd, Cheltenham, UK, pp. 1–14.

Brown, M.T., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9, 51–69.

Brown, M.T., Ulgiati, S., 2004. Energy quality, emergy, and transformity: h.T. Odum’s contributions to quantifying and understanding systems. Ecol. Model. 178, 201–213.

Brown, M.T., Campbell, D.E., De Vilbiss, C., Ulgiati, S., 2016. The geobiosphere emergy baseline: a synthesis. Ecol. Model. 339, 92–95.

Buenfil, A.A., 2001. Emergy Evaluation of Water, Dissertation, University of Florida.

Campbell, D.E., Ohrt, A., 2009. Environmental Accounting Using Emergy: Evaluation of Minnesota. US Environmental Protection Agency, Washington.

Campbell, D.E., 2001. Proposal for including what is valuable to ecosystems in environmental assessments. Environ. Sci. Technol. 35, 2867–2873.

Campbell, D.E., 2016. Emergy baseline for the Earth: a historical review of the science and a new calculation. Ecol. Model. 339, 96–125.

Chen, B., Chen, G.Q., 2007. Resource analysis of the Chinese society 1980–2002 based on exergy. Energy Policy 35 (4), 2051–2086.

Chen, W.Q., Huang, D., Liu, N., Zhang, Y.J., Badgery, W.B., Wang, X.Y., Shen, Y., 2015. Improved grazing management may increase soil carbon sequestration in temperate steppe. Sci. Rep. 5, 10892.

Coppola, F., Bastianoni, S., Østergård, H., 2009. Sustainability of bioethanol production from wheat with recycled residues as evaluated by Emergy assessment. Biomass Bioenergy 33, 1626–1642.

Dong, X.B., Brown, M.T., Pfahler, D., Ingwersen, W.W., Kang, M., Jin, Y., Yu, B.H., Zhang, X.S., Ulgiati, S., 2012. Carbon modeling and emergy evaluation of grassland management schemes in Inner Mongolia. Agric. Ecosyst. Environ. 158, 49–57.

Dong, X.B., Yu, B.H., Brown, M.T., Zhang, Y.S., Kang, M.Y., Jin, Y., Zhang, X.S., Ulgiati, S., 2014. Environmental and economic consequences of the overexploitation of natural capital and ecosystem services in Xilinguole League, China. Energy Policy 67, 677–780.

Feng, T.F., Sun, L.Y., Zhang, Y., 2009. The relationship between energy consumption structure, economic structure and energy intensity in China. Energy Policy 32 (12), 5475–5483.

Geng, Y., Sarkis, J., Ulgiati, S., Zhang, P., 2013. Measuring China’s circular economy. Science 339, 1526–1527.

Ghaley, B.B., Porter, J.R., 2013. Emergy synthesis of a combined food and energy production system compared to a conventional wheat (*Triticum aestivum*) production system. Ecol. Indic. 24, 534–542.

Ji, X., Chen, G.Q., 2006. Exergy analysis of energy utilization in the transportation sector in China. Energy Policy 34 (14), 1709–1719.

Kemp, D.R., Han, G.D., Hou, X.Y., Michalk, D.L., Hou, F.J., Wu, J.P., Zhang, Y.J., 2013. Innovative grassland management systems for environmental and livelihood benefits. Proc. Natl. Acad. Sci. U. S. A. 110 (21), 8369–8374.

Krausmann, F., Erb, K.H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. Proc. Natl. Acad. Sci. U. S. A. 110 (21), 10324–10329.

Lan, S.F., Qin, P., Lu, H.F., 2002. Emergy Assessment of Eco-ecological Systems. Press, Chemical Industry, Beijing, China (in Chinese).

Li, L.J., Lu, H.F., Tilley, D.R., Qiu, G.Y., 2014. Effect of time scale on accounting for renewable emergy in ecosystems located in humid and arid climates. Ecol. Model. 287, 1–8.

Liu, J.Y., Kuang, W.H., Zhang, Z.X., Xu, X.L., Qin, Y.W., Ning, J., Zhou, W.C., Zhang, S.W., Li, R.D., Yan, C.Z., 2014. Spatiotemporal characteristics, patterns and causes of land use changes in China since the late 1980. J. Geogr. Sci. 24 (2), 195–210.

Liu, J.G., Mooney, H., Hull, V., Davis, S.J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K.C., Gleick, P., Kremen, C., Li, S.X., 2015. Systems integration for global sustainability. Science 347 (6225), 1258832.

Lu, H.F., Campbell, D.E., Li, Z.A., 2006. Emergy synthesis of an agro-forest restoration system in lower subtropical China. Ecol. Eng. 27, 175–192.

Lu, H.F., Bai, Y., Ren, H., Campbell, D.E., 2010. Integrated emergy, energy and economic evaluation of rice and vegetable production systems in alluvial paddy fields: implications for agricultural policy in China. J. Environ. Manage. 91, 2727–2735.

Ma, F.J., Eneji, A.E., Liu, J.T., 2014. Understanding relationships among agro-ecosystem services based on emergy analysis in luancheng county, North China. Sustainability 6, 8700–8719.

Martin, J.F., Diemont, S.A.W., Powell, E., Stanton, M., Levy-Tacher, S., 2006. Emergy evaluation of the performance and sustainability of three agricultural systems with different scales and management. Agric. Ecosyst. Environ. 115 (1–4), 128–140.

Meyfroidt, P., Lambin, E.F., Erb, K., Hertel, T.W., 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. Curr. Opin. Environ. Sust. 5, 1–7.

Mooney, H.A., Duraiappah, A., Larigauderie, A., 2013. Evolution of natural and social science interactions in global change research programs. Proc. Natl. Acad. Sci. U. S. A. 110 (Suppl.1), 3665–3672.

Odum, H.T., 1988. Self-organization transformity, and information. Science 242, 1132–1139.

Patrizia, G., Zucaro, A., Viglia, S., Ulgiati, S., 2014. Monitoring and evaluating thesustainability of Italian agricultural system. An emergy decomposition analysis. Ecol. Model. 271, 132–148.

Rindfuss, R., Walsh, S., Turner, B.L., Fox, J., Mishra, V., 2004. Developing a science of land change: challenges and methodological issues. Proc. Natl. Acad. Sci. U. S. A. 101, 13976–13981.

Rydberg, T., Haden, A.C., 2006. Emergy evaluations of Denmark and Danish agriculture: assessing the influence of changing resource availability on the organization of agriculture and society. Agric. Ecosyst. Environ. 117, 145–158.

Soliveres, S., Smit, C., Maestre, F.T., 2015. Moving forward on facilitation research: response to changing environments and effects on the diversity, functioning and evolution of plant communities. Biol. Rev. 90, 297–313.

Tao, J., Fu, M., Zheng, X., Zhang, J., Zhang, D., 2013. Provincial level-based emergyevaluation of crop production system and development modes in China. Ecol. Indic. 29, 325–338.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1994. Emergy use, environmental loading and sustainability: an emergy analysis of Italy. Ecol. Model. 73, 215–268.

Ulgiati, S., Bargigli, S., Raugei, M., 2007. An emergy evaluation of complexity, information and technology, towards maximum power and zero emissions. J. Cleaner Prod. 15, 1359–1372.

Wang, X.Y., Zhang, Y.J., Huang, D., Li, Z.Q., Zhang, X.Q., 2015. Methane uptake and emissions in a typical steppe grazing system during the grazing season. Atmos. Environ. 105, 14–21.

Wright, C., Østergård, H., 2016. Renewability and emergy footprint at different spatial scales forinnovative food systems in Europe. Ecol. Indic. 62, 220–227.

Zhang, M.A., Borjigin, E., Zhang, H.P., 2007. Mongolian nomadic culture and ecological culture: on the ecological reconstruction in the agro-pastoral mosaic zone in Northern China. Ecol. Eco. 62 (1), 19–26.

Zhang, Y., Yang, Z., Liu, G., Yu, X., 2011. Emergy analysis of the urban metabolism of Beijing. Ecol. Model. 222, 2377–2384.

Zhang, X.H., Zhang, R., Wu, J., Zhang, Y.Z., Lin, L.L., Deng, S.H., Li, L., Yang, G., Yu, X.Y., Qi, H., Peng, H., 2016. An emergy evaluation of the sustainability of Chinese crop production system during 2000–2010. Ecol. Indic. 60, 622–633.

Zhao, H.L., Zhao, X.Y., Zhang, T.H., Zhou, R.L., 2002. Boundary line on agro-pasture zigzag zone in north China and its problems on Eco-environment. Adv. Earth Sci. 17 (5), 739–747 (in Chinese with English abstract).

Zheng, S.H., Wang, K., Zhao, M.L., Han, G.D., Feng, Y.F., 2009. Primary evaluation of the indirect value on rangeland ecosystem services in Northern agro-pastoral ecotone – a case study in Taipusi banner and Guyuan league. Pratacultural Sci 26 (9), 18–23 (in Chinese with English abstract).