

The emergy of metabolism in the same ecosystem (maize) under different environmental conditions

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ARTICLE INFO

Article history:

Received 22 November 2017

Received in revised form

22 March 2018

Accepted 23 April 2018

Available online 23 April 2018

Keywords:

Emergy evaluation

Ecosystem

Environment

Maize

ABSTRACT

Ecosystem sustainability is the basis for life, economic and social sustainability. The energy metabolism of an ecosystem has long been a focus area in the scientific community because it determines the productivity, sustainability and development of ecosystem. This study applied emergy analysis to explore the metabolism of maize ecosystems under different environmental conditions; to investigate its energy input, environmental pressure and sustainability; and to understand the maintenance mechanism of the general ecosystem based on the China statistical data of 2014. Results showed that the sum of renewable natural resources ranged from 0.62×10^{14} sej/ha in Xinjiang to 6.34×10^{14} sej/ha in Guangxi; the sum of nonrenewable natural resources ranged from 3.95×10^{14} sej/ha for Henan to 9.46×10^{14} sej/ha for Jilin; the sum of purchased renewable resources ranged from 2.97×10^{14} sej/ha for Heilongjiang to 26.14×10^{14} sej/ha for Gansu; the sum of purchased nonrenewable resources ranged from 14.89×10^{14} sej/ha in Sichuan to 33.00×10^{14} sej/ha in Gansu. In addition, the environmental loading ratio in Xinjiang was the highest, followed by Ningxia (25.92), Gansu (24.77), Inner Mongolia (23.15), the lower values were 4.48, 4.21 and 4.00 for Guizhou, Chongqing and Guangxi, respectively; similarly, the emergy sustainability index in the provinces of southern China were higher than those in northwest of China. Above all, maize ecosystem is developed with a stronger competitive ability than other agricultural ecosystems, especially in the southern region of China, but also has a high environmental loading ratio. Furthermore, the proportion of natural and purchased emergy input ranged from 13.65% vs 86.35% in Xinjiang to 33.70% vs 66.30% in Heilongjiang, which were close to 30% vs 70%, 25% vs 75%, 22% vs 78%, 20% vs 80% and 15% vs 85% for Northeast of China, Southwest of China, Loess Plateau, Huang-Huai-Hai Plain and Northwest of China respectively. Our study demonstrates that the natural energy in the maize ecosystem influenced the quantity and proportion of purchased energy. Different combinations of natural and purchased emergy were coupled to maintain the same ecosystem under the different environmental conditions. Its recommendation is to consider changing the crop production systems or artificial energy inputs in different regions based on differences in natural factors in order to make more efficient use of resources, reduce the use of chemical fertilizers, and promote the sustainability of ecosystems.

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1. Introduction

Ecosystem ecology has become the focus field to study life processes and phenomena since Sir Arthur Tansley proposed the concept of ecosystem (Tansley, 1939). Driven by both natural factors and anthropogenic impacts, ecosystems are always in constant

change in the real world especially those ecosystems with human disturbance (Andela et al., 2017; Bürgi et al., 2017; Kareiva et al., 2007; Pecl et al., 2017; Steffen et al., 2015). Owing to ever-increasing resource uses, the agricultural ecosystem provides food and clothing for people while at the same time, influencing ecosystem processes such as land use change, freshwater use, and nitrogen and phosphorus loads (Steffen et al., 2015). On the one hand it exemplifies the coexistence of multiple or diversified agricultural ecosystems under local scales because of different energy inputs and compositions (Kremen and Miles, 2012; Zhai et al., 2017;

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Zhang et al., 2012). On the other hand, the same agro-ecosystem can be maintained at larger scales or under different climatic conditions, such as those for maize (He and Zhou, 2016; Lesk et al., 2016; Schlenker and Roberts, 2009; Tao et al., 2016).

In China, maize is cultivated throughout a large region from northeast to southwest China. Its cultivation area and annual yield have both ranked first out of China's cereal crops since 2012 (Zhang et al., 2017), with the climate-suitable planting area for summer maize approaching about 1.6×10^8 hm² in the last 10 years (He and Zhou, 2016). China produces more than 20% of global annual maize and is the second consumer of maize in the world (Tao et al., 2016). How can the same maize agro-ecosystem be maintained under different environmental conditions?

Many studies have conducted research on maize production and its relationship with climate change (Schlenker and Roberts, 2009; Tao et al., 2016), extreme weather (Lesk et al., 2016) and phenotypic and genetic change during the domestication process (Piperno, 2017). Nowadays, with the Green Revolution, agricultural or crop intensification has resulted in a dramatic increase in commercial non-renewable energy use (Pimentel, 2009; Rydberg and Haden, 2006). Sustainable agricultural ecosystems face great challenges in the world including those in China (Chen et al., 2014; Tilman et al., 2011; Zhang et al., 2016a). Increasingly scientists have focused on how to produce more grain and how to reduce inputs to lower environmental costs and improve agricultural sustainability (Chen et al., 2014; Jez et al., 2016). For example, the Science and Technology Backyard (STB) platform, which involves agricultural scientists living in villages among farmers, advances participatory innovation and technology transfer, and garners public and private support has been successful in documenting yield and economic gains of maize production in some Chinese provinces (Zhang et al., 2016a).

A holistic approach coupling human and natural systems is necessary to address complex interconnections and identify effective solutions to sustainability challenges (Fan et al., 2018; Liu et al., 2015). Therefore we ask, “what are the characteristics of energy metabolism in the maize ecosystem of China, and does energy metabolism vary across the ecosystem, and if so, why?”. The Maize ecosystem is a complex system that combines natural ecology and social economy, and emergy theory or evaluation has been an important measure for assessing the energy metabolism and sustainability of agricultural systems (Ghaley and Porter, 2013; Houshyar et al., 2018; Odum, 1988; Wang et al., 2015, 2017). In this study, therefore, the emergy of metabolism in the maize ecosystem of China was examined as a case study to find consistencies, differences and characteristics of emergy input, to understand the maintenance mechanism, and to discuss its sustainability under different environmental conditions.

2. Materials and methods

2.1. Data collection and sources

In this study, twenty provinces of China were chosen as research regions having the main corn planting area, and the related land use data were based on the China Statistical Yearbook (CSY, 2015). The corresponding data sources were mainly from the National Agricultural Product Cost Income Data Compilation (NAPCIDC, 2015), China Climate Impact Assessment (CCIA, 2014), Xinjiang Statistical Yearbook (XSY, 2015) and the study by Tao et al. (2013).

Eighteen different input flows distributed into four categories: Renewable natural resources (R), nonrenewable natural resources (N), purchased renewable resources (PR) and purchased nonrenewable resources (PN) emergy (Table 1). Renewable natural energy includes sun, wind, rain and earth cycle, because they were co-

products of coupled processes according to emergy theory. The energy input of rain, which constituted the highest emergy flow of the four, was considered to be the entire renewable resource emergy flow to avoid overestimating renewable inputs. Nonrenewable natural energy input was net loss of topsoil. Purchased renewable energy includes irrigating water, human labor, livestock labor, manure and seeds; non-renewable purchased energy includes nitrogen fertilizer, phosphate fertilizer, potash fertilizer, compound fertilizer, pesticides, diesel and capital investment.

2.2. Data statistics and analysis

Emergy synthesis is an accounting tool which takes into account both the environment and the economic inputs into a production system. The maize ecosystem boundary is defined to assess the inputs and outputs according to the emergy synthesis (Fig. 1). Emergy is described as the available energy of one kind previously required directly and indirectly to perform a service or product. It is a solar equivalent joule of available energy that has been used in the past to create a product or service (Odum, 1996). Solar emjoules can be used to quantify all products of the transformations of available energy delivered to the geobiosphere through the planetary baseline (Campbell, 2016). The units given in joules and grams were then multiplied by Unit Emergy Value (UEV) 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 (Table 2) $\times$ UEV (Campbell, 2001; Odum, 1988). Conversion of the different flows into emergy was done with reference to the geobiosphere emergy baseline of $12.1 \text{ E}+24$ sej/year (Brown et al., 2016; Campbell, 2016); therefore, the UEV data from other studies which were relative to the $9.26\text{E}+24$ and $15.83\text{E}+24$ sej/year baseline were converted to the $12.1 \text{ E}+24$ sej/year by multiplying by a conversion factor of 1.3 and 0.758 (Table 1).

3. Results

3.1. Energy flows and emergy indicators of maize ecosystem

The energy systems language diagram of the maize production system is presented in Fig. 1 with the main fluxes and components,

Table 1
Unit Emergy Value (UEV) of different inputs for maize ecosystem.

No.	Item	Units	UEV (sej/unit)	References
Renewable natural resources(R)				
1	Sunlight	J	1.00E+00	Odum (1996)
2	Wind, kinetic energy	J	3.14E+03	Odum (2000)
3	Rain	J	2.33E+04	Odum (1996)
4	Earth cycle	J	7.42E+04	Odum (2000)
Nonrenewable natural resources(N)				
5	Net loss of topsoil	J	9.47E+04	Brown and Bardi (2001)
Purchased nonrenewable resources (PN)				
6	Nitrogen fertilizer	g	4.86E+09	Odum (1996)
7	Phosphate fertilizer	g	4.99E+09	Odum (1996)
8	Potash fertilizer	g	1.41E+09	Odum (1996)
9	Compound fertilizer	g	3.58E+09	Odum (1996)
10	Pesticides	g	2.05E+09	Odum (1996)
11	Diesel	J	8.45E+04	Odum (1996)
12	Capital investment	\$	1.92E+12	Brown and Bardi (2001)
Purchased renewable resources (PR)				
13	Irrigating water	J	5.25E+04	Odum and Arding (1991)
14	Human labor	J	4.86E+05	Lan et al. (1998)
15	Livestock labor	J	1.87E+05	Lan et al. (1998)
16	Manure	g	1.62E+08	Bastianoni et al. (2001)
17	Seeds	g	9.14E+08	Coppola et al. (2009)

Note: All these UEVs have been corrected according to the baseline $12.1 \text{ E}+24$ sej/year (Brown et al., 2016; Campbell, 2016).

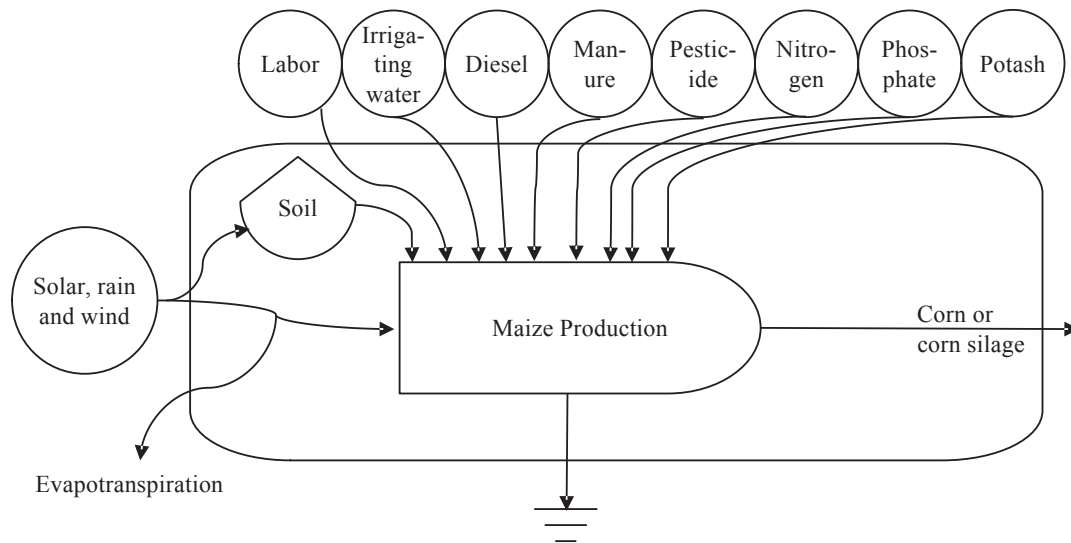


Fig. 1. A general energy flow diagram of the maize production system in China. —→ Energy circuit. A pathway whose flow is proportional to the storage. ○ Constant force source. ⬡ Storage. □ Producer. ⬇ Heat sink. □ System frame.

as well as relations among them. The main categories of energy, energy flows into the maize ecosystem and arable land area, were summarized in Tables 2–1 and 2–2. Table 3 lists the emery inputs and categorizes them as renewable natural resources (R), nonrenewable natural resources (N), purchased renewable resources (PR) and purchased nonrenewable resources (PN) emery. For comparison, all flows were expressed in units of annual solar energy (sej) per hectare. There was a variance in total emery input, ranging from 31.91×10^{14} sej/ha in Henan to 69.17×10^{14} sej/ha in Gansu. The PN input makes the largest contribution to the total input except from Chongqing, Yunnan and Guizhou, followed by the PR input, then the N input, and the R input has the smallest contribution. The sum of R ranged from 0.62×10^{14} sej/ha in Xinjiang to 6.34×10^{14} sej/ha in Guangxi; the sum of N ranged from 3.95×10^{14} sej/ha for Henan to 9.46×10^{14} sej/ha for Jilin. The value of purchased emery inputs changed from 21.68×10^{14} sej/ha (Heilongjiang) to 59.14×10^{14} sej/ha (Gansu). The sum of PR in which ranged from 2.97×10^{14} sej/ha for Heilongjiang to 26.14×10^{14} sej/

ha for Gansu; the sum of PN in which ranged from 14.89×10^{14} sej/ha in Sichuan to 33.00×10^{14} sej/ha in Gansu.

For emery-based indicators (Table 4), the emery investment ratio (EIR) gives an evaluation if the process is a good user of the emery that is invested, in comparison with alternatives. The emery yield ratio (EYR) is an indicator of the yield compared to inputs other than local and gives a measure of the ability of the process to exploit local resources. The environmental loading ratio (ELR) is an indicator of the pressure of the process on the ecosystem due to a production activity (Brown and Ulgiati, 1997). The emery sustainability index (ESI) measures the potential contribution of a resource or process to the economy per unit of environmental loading (Ulgiati and Brown, 1998). The lowest EIR value was 1.97 in Heilongjiang, and the EIR values in Xinjiang (6.32) and Gansu (5.90) were higher than those of the other provinces. Guizhou and Henan were the provinces with the highest and lowest EYR values. The ELR value in Xinjiang was the highest, followed by Ningxia (25.92), Gansu (24.77), Inner Mongolia (23.15). The lower ELR values were

Table 2-1
Energy input, output and planting area of maize ecosystem for each province (2014).

No.	Item	Units	Hebei	Shanxi	Inner Mongolia	Liaoning	Jilin	Heilongjiang	Jiangsu	Anhui	Shandong	Henan
1	Sunlight	J	5.16E+19	2.77E+19	5.57E+19	3.80E+19	6.12E+19	8.92E+19	7.12E+18	1.39E+19	5.09E+19	5.38E+19
2	Wind energy	J	2.88E+16	1.54E+16	3.10E+16	2.11E+16	3.40E+16	4.97E+16	3.95E+15	7.76E+15	2.83E+16	2.99E+16
3	Rain	J	2.05E+16	1.47E+16	1.86E+16	1.65E+16	3.12E+16	5.09E+16	7.99E+15	1.80E+16	2.66E+16	3.76E+16
4	Earth cycle	J	2.32E+14	1.24E+14	2.50E+14	1.71E+14	2.75E+14	3.99E+14	3.19E+13	6.25E+13	2.28E+14	2.41E+14
5	Net loss of topsoil	J	1.77E+16	1.48E+16	2.97E+16	2.15E+16	3.69E+16	5.05E+16	2.27E+15	4.49E+15	1.62E+16	1.37E+16
6	Nitrogen fertilizer	g	3.03E+11	1.92E+11	4.99E+11	2.47E+11	2.33E+11	5.63E+11	9.85E+10	1.42E+11	3.85E+11	2.82E+11
7	Phosphate fertilizer	g	2.85E+09	4.53E+09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.31E+09	1.66E+09	0.00E+00	0.00E+00
8	Potash fertilizer	g	0.00E+00	0.00E+00	2.53E+09	0.00E+00	2.66E+10	7.26E+10	0.00E+00	0.00E+00	1.41E+09	0.00E+00
9	Compound fertilizer	g	6.62E+11	4.45E+11	7.03E+11	7.05E+11	1.30E+12	1.08E+12	8.56E+10	1.92E+11	8.90E+11	8.18E+11
10	Pesticides	g	1.25E+10	4.14E+09	1.19E+10	8.38E+09	1.80E+10	1.96E+10	2.21E+09	4.03E+09	1.63E+10	1.58E+10
11	Diesel	J	0.00E+00	1.52E+14	0.00E+00	0.00E+00	1.03E+14	0.00E+00	0.00E+00	1.14E+13	6.84E+14	0.00E+00
12	Capital investment	\$	1.09E+09	5.84E+08	1.25E+09	5.81E+08	1.29E+09	1.79E+09	8.17E+07	1.60E+08	1.15E+09	1.14E+09
13	Irrigating water	J	0.00E+00	0.00E+00	2.12E+15	0.00E+00	0.00E+00	7.48E+13	5.44E+13	0.00E+00	4.30E+14	0.00E+00
14	Human labor	J	3.39E+15	2.38E+15	2.49E+15	2.13E+15	3.81E+15	3.00E+15	5.10E+14	8.38E+14	3.23E+15	3.43E+15
15	Livestock labor	J	3.48E+12	5.48E+12	3.12E+12	7.49E+13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.45E+11	0.00E+00
16	Manure	g	3.84E+12	6.21E+12	1.89E+12	2.72E+12	1.86E+12	4.90E+10	2.88E+11	3.53E+11	7.10E+12	0.00E+00
17	Seeds	g	1.12E+11	4.00E+10	1.16E+11	7.76E+10	1.10E+11	1.59E+11	1.38E+10	2.56E+10	9.75E+10	1.09E+11
18	Corn	J	3.20E+17	2.01E+17	3.92E+17	2.31E+17	4.07E+17	5.78E+17	4.52E+16	8.67E+16	3.59E+17	3.28E+17
19	Arable land area	ha	3.17E+06	1.68E+06	3.37E+06	2.33E+06	3.70E+06	5.44E+06	4.36E+05	8.52E+05	3.13E+06	3.28E+06

Table 2–2

Energy input, output and planting area of maize ecosystem for each province (2014).

No.	Item	Units	Hubei	Guangxi	Chongqing	Sichuan	Guizhou	Yunnan	Shaanxi	Gansu	Ningxia	Xinjiang
1	Sunlight	J	1.61E+20	9.95E+19	6.33E+19	1.92E+20	9.53E+19	1.27E+20	9.56E+19	9.35E+19	2.79E+19	1.14E+20
2	Wind energy	J	8.96E+16	5.53E+16	3.52E+16	1.06E+17	5.29E+16	7.03E+16	5.31E+16	5.19E+16	1.55E+16	6.30E+16
3	Rain	J	3.53E+16	4.53E+16	2.94E+16	6.42E+16	5.16E+16	7.09E+16	3.77E+16	1.99E+16	4.49E+15	6.31E+15
4	Earth cycle	J	7.24E+14	4.47E+14	2.84E+14	8.61E+14	4.27E+14	5.68E+14	4.29E+14	4.19E+14	1.25E+14	5.10E+14
5	Net loss of topsoil	J	5.08E+16	4.60E+16	2.44E+16	6.48E+16	4.89E+16	6.62E+16	4.41E+16	5.08E+16	1.21E+16	4.50E+16
6	Nitrogen fertilizer	g	1.15E+11	1.49E+11	8.10E+10	1.90E+11	1.51E+11	4.07E+11	2.94E+11	2.41E+11	6.23E+10	2.05E+11
7	Phosphate fertilizer	g	9.15E+09	5.43E+09	1.14E+10	2.20E+10	2.81E+10	5.06E+10	8.48E+09	3.50E+10	0.00E+00	0.00E+00
8	Potash fertilizer	g	8.67E+08	4.47E+09	0.00E+00	0.00E+00	1.18E+08	1.14E+09	0.00E+00	3.00E+09	0.00E+00	2.87E+09
9	Compound fertilizer	g	1.24E+11	6.19E+10	6.46E+10	1.67E+11	5.50E+10	1.29E+11	1.46E+11	1.65E+11	7.38E+10	2.01E+11
10	Pesticides	g	2.56E+09	4.40E+08	1.65E+09	4.56E+09	1.92E+09	8.50E+09	3.25E+09	2.10E+09	1.71E+09	2.74E+09
11	Diesel	J	3.66E+14	1.50E+14	1.07E+14	0.00E+00	4.35E+14	0.00E+00	0.00E+00	9.15E+13	0.00E+00	2.56E+14
12	Capital investment	\$	7.27E+07	3.55E+07	1.10E+07	1.85E+08	7.50E+07	1.37E+08	4.37E+08	4.69E+08	1.12E+08	4.61E+08
13	Irrigating water	J	0.00E+00	0.00E+00	0.00E+00	2.19E+14	0.00E+00	8.19E+13	0.00E+00	1.26E+15	5.20E+14	6.05E+14
14	Human labor	J	9.77E+14	1.03E+15	1.13E+15	2.66E+15	1.92E+15	3.73E+15	2.00E+15	2.78E+15	3.96E+14	8.06E+14
15	Livestock labor	J	2.88E+13	4.97E+13	9.68E+12	5.11E+13	7.99E+13	1.35E+14	1.26E+13	3.76E+12	0.00E+00	3.41E+12
16	Manure	g	1.47E+12	2.68E+12	1.34E+12	2.96E+12	3.29E+12	9.92E+12	1.91E+12	7.17E+12	6.87E+11	4.20E+12
17	Seeds	g	1.67E+10	1.59E+10	9.90E+09	4.23E+10	1.77E+10	5.15E+10	4.69E+10	3.93E+10	1.07E+10	4.28E+10
18	Corn	J	4.93E+16	4.27E+16	3.97E+16	1.24E+17	6.23E+16	1.33E+17	1.05E+17	1.30E+17	3.56E+16	1.32E+17
19	Arable land area	ha	6.42E+05	5.84E+05	4.68E+05	1.38E+06	7.88E+05	1.53E+06	1.15E+06	1.00E+06	2.89E+05	9.11E+05

Table 3

Emergy inputs of maize ecosystem for each province.

Provinces	R (*E+14 sej/ha)	N (*E+14 sej/ha)	PR (*E+14 sej/ha)	PN (*E+14 sej/ha)	U (*E+14 sej/ha)
Hebei	1.56	5.28	7.48	18.93	33.25
Shanxi	2.10	8.34	13.12	22.48	46.04
Inner Mongolia	1.34	8.35	5.14	22.67	37.50
Liaoning	1.71	8.75	6.70	20.86	38.02
Jilin	2.02	9.46	6.09	22.58	40.15
Heilongjiang	2.23	8.79	2.97	18.71	32.70
Jiangsu	4.32	4.92	7.11	21.87	38.22
Anhui	4.98	4.99	5.72	20.03	35.72
Shandong	2.04	4.92	9.06	23.54	39.56
Henan	2.72	3.95	5.38	19.86	31.91
Hubei	4.51	4.92	11.43	19.26	40.12
Guangxi	6.34	7.19	16.45	18.14	48.12
Chongqing	5.14	5.98	16.63	15.64	43.39
Sichuan	3.82	5.28	13.26	14.89	37.25
Guizhou	5.36	7.98	18.99	16.04	48.37
Yunnan	3.82	8.17	22.93	20.83	55.75
Shaanxi	2.70	7.18	11.49	24.59	45.96
Gansu	1.67	8.36	26.14	33.00	69.17
Ningxia	1.32	6.78	11.81	27.44	47.35
Xinjiang	0.62	6.21	12.55	30.64	50.02

4.48, 4.21 and 4.00 for Guizhou, Chongqing and Guangxi, respectively. The ESI value is the ratio of EYR to ELR, can be divided into four groups. Group 1 comprised of Guizhou, Chongqing and Guangxi, had the highest ESI (0.66–0.67), then Sichuan, Hubei, Yunnan, Anhui and Jiangsu (0.28–0.47), followed by Henan, Shaanxi, Shanxi, Heilongjiang, Shandong, Liaoning, Jilin and Hebei (0.11–0.18), and the lowest group included Gansu, Ningxia, Inner Mongolia and Xinjiang (0.03–0.08).

3.2. Emergy input characteristics in China's maize growing areas

The variation in natural and purchased emergy inputs together sustains the existence of the maize ecosystem under different environmental conditions in the main growing provinces. The proportion of natural and purchased emergy input ranged from 13.65% vs 86.35% in Xinjiang to 33.70% vs 66.30% in Heilongjiang (Figs. 2 and 3). To assess the regularity and characteristics of maize ecosystem emergy metabolism in different regions, factors such as geography, climate, and the maize production zones of China (Tao et al., 2016) were used to group fourteen selected representative provinces into five regional areas: Northeast of China (NE), Loess

Plateau (LP), Northwest of China (NW), Huang-Huai-Hai Plain (HP) and Southwest of China (SW). The NE included Heilongjiang, Jilin and Liaoning; the LP was comprised of Shaanxi and Shanxi; the NW consisted of Gansu, Ningxia and Xinjiang; the HP consisted of Hebei, Henan and Shandong; and the SW included Guizhou, Sichuan and Yunnan. The average proportion of natural emergy input decreased gradually from NE, SW, LP, HP and then to NW. Conversely, the average proportion of purchased emergy input increased from 70.07% to 84.91% in the same order (Table 5), the gap between the NE and NW was close to 15%.

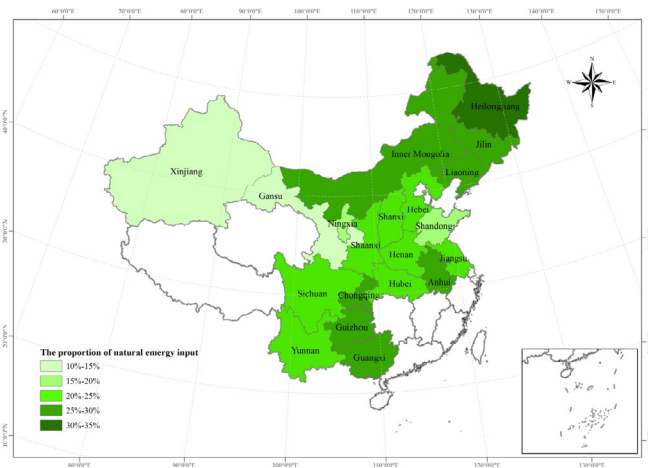
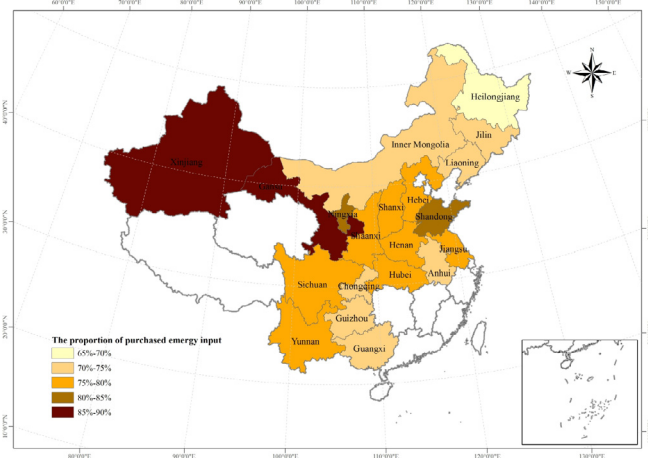
4. Discussion

Environmental heterogeneity is a universal driver of species richness across natural ecosystems (Stein et al., 2014), however, the positive heterogeneity-richness relationships are changed by anthropogenic material or energy input in agricultural ecosystems. The maize ecosystem is a human-controlled ecosystem, which relies on both the natural inputs (such as sun, rain, wind and the soil, etc.) and the purchased energy inputs (such as diesel, electricity, fertilizers and labor, etc.). In this study, the purchased emergy input

Table 4

Energy indices of maize ecosystem for each province.

Provinces	Emergy investment ratio (EIR)	Emergy yield ratio (EYR)	Environmental loading ratio (ELR)	Emergy sustainability index (ESI)
Parameters	$(PR+PN)/(R+N)$	U/PN	$(N+PN)/R$	EYR/ELR
Hebei	3.86	1.76	15.52	0.11
Shanxi	3.41	2.05	14.68	0.14
Inner Mongolia	2.87	1.65	23.15	0.07
Liaoning	2.63	1.82	17.32	0.11
Jilin	2.50	1.78	15.86	0.11
Heilongjiang	1.97	1.75	12.33	0.14
Jiangsu	3.14	1.75	6.20	0.28
Anhui	2.58	1.78	5.02	0.35
Shandong	4.68	1.68	13.95	0.12
Henan	3.78	1.61	8.75	0.18
Hubei	3.25	2.08	5.36	0.39
Guangxi	2.56	2.65	4.00	0.66
Chongqing	2.90	2.77	4.21	0.66
Sichuan	3.09	2.50	5.28	0.47
Guizhou	2.63	3.02	4.48	0.67
Yunnan	3.65	2.68	7.59	0.35
Shaanxi	3.65	1.87	11.77	0.16
Gansu	5.90	2.10	24.77	0.08
Ningxia	4.84	1.73	25.92	0.07
Xinjiang	6.32	1.63	59.44	0.03

**Fig. 2.** The proportion of natural energy input in the main maize growing provinces.**Fig. 3.** The proportion of purchased energy input in the main maize growing provinces.

made the largest contribution to the total input (66%–86% in our study), which is higher than the average energy input of 57% in

Table 5

Natural and purchased energy input ratios in major maize planting areas of China.

Regional scale	Natural energy input ratio (%)	Purchased energy input ratio (%)
Northeast of China	29.93%	70.07%
Southwest of China	24.51%	75.49%
Loess Plateau	22.09%	77.91%
Huang-Huai-Hai Plain	19.69%	80.31%
Northwest of China	15.09%	84.91%

China's agriculture ecosystem (Chen et al., 2006), but lower than in China's crop production system (86%–89%) including rice, wheat, corn, beans, tubers, cotton, peanuts, rape seed, sugarcane, beet-roots, fruits and vegetables (Zhang et al., 2016b). On the other hand, there are some differences among emergy inputs and indicators of the maize ecosystem at local and regional scale. Zhenfeng County, a karst area of Guizhou Province (Cheng et al., 2017), with values lower than our data in Guizhou Province, including lower percentage of natural renewable resources among total inputs (4.7% vs 11.1%), lower emergy self-sufficiency ratio (0.06 vs 0.28), environmental loading ratio (2.60 vs 4.48) and lower emergy sustainability index (0.42 vs 0.67). These results indicated that there are some variations between natural resources, climatic conditions and purchased energy inputs at local versus larger scales (Yu et al., 2016). Above all, this phenomenon is similar to the atomic structure in physics, here we called it “Ecosystem Core”. The natural resource is the nucleus, and the purchased energy is like the extra-nuclear electron. The natural energy determines the quantity and proportion of purchased energy. These two energies are coupled together through different combinations to maintain the same ecosystem under the different environmental conditions. In this study, the proportions of natural energy vs purchased energy were close to 30% vs 70%, 25% vs 75%, 22% vs 78%, 20% vs 80% and 15% vs 85% for NE, SW, LP, HP and NE respectively.

Except for Henan (1.61), Inner Mongolia (1.65), Shandong (1.68) and Xinjiang (1.63), the EYR values were higher than the average of China's crop production system (1.68, Zhang et al., 2016b), 1.07 and 1.17 for corn production in the USA and Italy, respectively (Martin et al., 2006; Patrizia et al., 2014). These results showed that the maize ecosystem has a stronger competitive ability than other agricultural ecosystem, especially in the southern region of China.

All ESI values of less than 1 meet the classification of a “developed” economy for the maize ecosystem in China (Brown and Ulgiati, 1997). Renewable resources are very important to sustainable development, however, the use of nonrenewable resources speeds up the wealth of a country but undermines its long term sustainability (Liu et al., 2016; Yu et al., 2016), with the ELR values much higher than the national average (2.10, Zhang et al., 2016b), especially the provinces of northwest of China. In the future, intercropping involving two or more crop species (Brooker et al., 2015) or diversified farming systems (Cheng et al., 2017; Kremen and Miles, 2012) with enough consideration on environmental degradation may be the right choice for developing a sustainable agricultural ecosystem to balance crop production, environmental resource consumption and ecosystem services.

5. Conclusion

Natural and purchased emergy input should be considered together in different combinations to sustain the existence of the maize ecosystem under varying environmental conditions. The proportion of natural energy was much less than purchased energy in all 5 regions, the proportion of natural energy vs purchased energy decreased gradually from NE, SW, LP, HP and then to NW. These emergy indicators indicated that maize ecosystem is developed with a stronger competitive ability than other agricultural ecosystems, especially in the southern region of China, but also has a high environmental loading ratio. In addition, we should consider changing the crop production systems or artificial energy inputs in different regions based on differences in natural factors in order to make more efficient use of resources, reduce the use of chemical fertilizers, and promote the sustainability of ecosystems.

Author contributions

W.K., Z.X.J. and Z.H. designed research; Z.X.J., Z.H., G.L.Z., H.D., L.K.S., T.S.M., Y.Y.J., G.J.X., L.J.H. and X.S. performed research; Z.H. and Z.X.J. analyzed data; and Z.X.J., F.D.M. and W.K. wrote the paper.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

We thank Dr. Paulette Ford for her kind guidance and advice for the first draft. Special thanks to Mr. Kai Liu for his technical help in Figures. We also acknowledge anonymous referees for their careful review and helpful comments on a preliminary version of this paper.

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