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Comparing protected cucumber and field cucumber production systems in China based on emergy analysis

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A B S T R A C T

Cucumber is an important vegetable, which provides essential minerals, vitamins and nutrients for human body and is widely cultivated in China on account of its delicious taste, short nutritional cycle and high economic benefits. To comprehensively evaluate the sustainability of the cucumber production systems under two planting patterns (the protected cucumber production system and the field cucumber production system), and to provide constructive suggestions for an efficient and sustainable development of the production systems, the emergy evaluation method was utilized to analyze the composition and metabolism of the emergy flows in the production systems based on 2016 provincial data from China. The results show that the mean value of natural resources input of the field cucumber production system (13.59E+14 sej/ha) was significantly higher than that of the protected cucumber production system (5.92E+14 sej/ha). However, the mean values of the purchased resources input, total emergy input and total energy output had the contrary trend. The extent to which the cucumber production systems under two planting patterns are dependent on the environment is different. The field cucumber production system uses more natural resources and the degree of utilization of natural resources is geographically distributed. More natural resources are utilized in the south of China where natural conditions are better. However, the protected cucumber production system uses more purchased resources, especially the nonrenewable resources, and has the characteristics of high input, high output but low production efficiency. Improving the efficiency of resources utilization, using more clean energy and improving the degree of mechanization will contribute to a cleaner, more efficient and sustainable development of the cucumber production system.

1. Introduction

Vegetables are one of the most basic food sources for human beings and provide nutrients such as vitamins, dietary fibers and minerals needed to maintain human health (Li et al., 2018). Data show that in 2017, the vegetable planting area in China reached 22.55 million ha, and vegetables have become the second largest crop after grain crops. Moreover, the annual gross output value of vegetables reached 2 trillion Yuan in 2017, and vegetable industry has become a pillar industry in rural areas. The vegetable industry plays an increasingly important and positive role in ensuring food safety, expanding employment in labor services, expanding international trade and stabilizing farmers' income (ECAEWMA, 2018).

The vegetable industry can be divided into protected vegetable or facility vegetable or installment vegetable industry and field vegetable or outdoor vegetable or open field vegetable industry according to the planting patterns (Gruda et al., 2019; Zhou et al., 2016; Cerkauskas et al., 2015). Protected vegetable industry is a kind of vegetable planting mode which depends on modern facilities such as greenhouse and supplementary light system to provide a relatively controllable closed or semi-closed space for production (Chang et al., 2011; Jiang, 2015). It frees agricultural production from the constraints of natural conditions to a certain extent, breaks the regional and seasonal constraints of traditional agriculture, thus increasing the time and variety of vegetables on the market, enriching people's “vegetable basket” in different seasons, and enriching people's “vegetable basket” in different

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regions (Wang et al., 2018a; Chen et al., 2018). However, the traditional field vegetable industry is greatly affected by natural environmental factors such as light, temperature and humidity (Khoshnevisan et al., 2014). Compared with the field vegetable industry, the protected vegetable industry has the characteristics of high input, high income, technology and capital intensive (Bolandnazar et al., 2014). Its production scale and efficiency are constantly developing, accounting for an increasing proportion of agricultural production. It is the future development direction of vegetable industry whether in China or in the world (Liang et al., 2019; Gruda et al., 2019). The planting area of protected vegetable industry increased from 15 000 ha in 1983 to 4 670 000 ha in 2010 in China, and it has been increasing in recent 10 years (Chen et al., 2013).

At the same time, with the continuous expansion of facility vegetable industry, it inevitably brings serious environmental damage, such as the generation of agricultural film waste (Stanghellini et al., 2003), groundwater pollution (Muñoz et al., 2008), greenhouse gas emissions (Chang et al., 2013), soil acidification, soil secondary salinization (Wang et al., 2018b), soil microbial flora destruction, soil nutrient imbalance, accumulation of harmful substances (Yang et al., 2015), soil-borne diseases and so on. Therefore, considering the good and bad aspects of greenhouse vegetable industry, it is very important to comprehensively measure the output of the greenhouse vegetable industry and its impact on the environment. What's more, it is indispensable to evaluate the sustainability of the greenhouse vegetable industry and provide corresponding countermeasures subsequently. Emergy analysis method put forward creatively by Odum (1984, 1988) satisfies these requirements very well. This analysis method can reveal the material circulation and energy flow in the protected vegetable production system, analyze the composition and metabolism of various resources input, and provide some indicators to evaluate the sustainability of the system for the convenience of giving constructive suggestions.

Since the advent of emergy analysis method, it has been widely used in the evaluation of agricultural systems (Zhao et al., 2019; Zhai et al., 2018), bioenergy production (Patrizi et al., 2015), circulatory systems (Saladini et al., 2016), urban systems (Andrić et al., 2017), industrial manufacturing (Mikulčić et al., 2016) and so on. However, only a few articles (Yang et al., 2016; Chang et al., 2011) have comprehensively analyzed the production process of the protected vegetable production system, and very few articles have evaluated its sustainability and compared it with field production system from the perspective of emergy.

Therefore, the cucumber production systems under two planting patterns in China were used as research examples to investigate the similarities and differences in resources input and output between the protected cucumber production system (PC) and the field cucumber production system (FC) by using emergy analysis in this paper. In addition, this study provided an overall framework for assessing the sustainability of the vegetable production systems through the use of a set of emergy indicators. Furthermore, based on the comprehensive performance of the production status of the vegetable production systems under different planting patterns and the factors affecting their sustainable development, some suggestions for formulating countermeasures and policies were given in this paper.

2. Materials and methods

2.1. Materials

This research was carried out based on the 2016 provincial data of those provinces with larger vegetable planting area and more convenient data collection. Input and output data of the protected cucumber production system of 21 Chinese provinces and data of the field cucumber production system of 26 Chinese provinces were mainly obtained from National Agricultural Product Cost Income Data Compilation (NDRCDP, 2017). Indeed, data of only 17 Chinese provinces with both production systems at the same time were used when these two systems were compared with each other. The corresponding meteorological data and natural resources input data were taken from China Water Statistical Yearbook (MWR, 2017) and a study carried out by Tao et al. (2013).

2.2. Research methods

As early as in 1980s, the famous American ecologist Odum had come up with a theory of emergy (Liu et al., 2019b). Emery is defined as the available energy needed directly or indirectly to manufacture a product or render a service (Odum, 1984, 1996). And emergy analysis is an effective method to evaluate the input and output of a system. It takes into account both the input of natural resources and the input of man-made resources and establishes a link between the human social system and the natural environment (Fang et al., 2017; Odum, 1996). All the primitive materials and energy of man-made systems including all kinds of agricultural production systems are derived from the biosphere (Liu et al., 2019a). Emergy analysis provides uniform metrics for describing the flow of energy, matter and currency in the system. In other words, different forms of materials (g), energy (J) and currency ($) can be translated uniformly into one familiar kind of energy such as solar emjoules (sej) by multiplying a conversion coefficient (Unit Emergy Value) in the emergy analysis method.

Unit Emergy Value (UEV) expressing solar emergy needed to provided 1 g, J or $ of a product or service is a key part of the method. The corresponding UEVs calculated by predecessors can be made use of when a specific system is assessed. However, there is a prerequisite that the UEVs adopted from previous studies are based on the same geobiosphere emergy baseline of 12.0E+24 sej/year in the latest research findings (Campbell, 2016; Brown and Ulgiati, 2016a). For instance, UEVs taken from studies based on the 9.26E+24, 9.44E+24 and 15.83E+24 sej/year geobiosphere emergy baseline should be converted into UEVs based on the 12.0E+24 sej/year baseline via multiplying the coefficient of 1.30, 1.27 and 0.76. The related UEVs obtained from previous researches has been already corrected (Table 1). Table 1 also indicates that the emergy input of the cucumber production systems can be divided into four categories generally: renewable natural resources (R); nonrenewable natural resources (N_0); nonrenewable purchased resources (FN); and renewable purchased resources (FR).

Within the framework of the emergy analysis, system diagrams associated with the cucumber production systems should be drawn firstly to present the process of emergy metabolism (Fig. 1). In addition, a set of emergy indices (Table 2) should be used to facilitate the evaluation of system sustainability.

3. Results

3.1. Emergy flows in different classifications for the cucumber production systems

Cucumber is widely cultivated in China. Specifically, the protected cucumber industry is mainly distributed in 21 provinces including Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Shandong, Henan, Hubei, Sichuan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang (Fig. 2a). And the field cucumber industry is mainly distributed in 26 provinces including Beijing, Tianjin, Hebei, Shanxi, Inner

Table 1
Emergy fluxes and related unit emergy values.

No.	Item	Units	Unit emergy value (sej/unit)	References
Renewable natural resources (R)				
1	Sunlight	J	1.00E+00	Odum (1996)
2	Earth cycle	J	4.90E+04	Brown and Ulgiati (2016b)
3	Rain, chemical potential	J	2.31E+04	Odum (1996)
4	Rain, geopotential	J	1.33E+04	Odum (1996)
5	Wind, kinetic energy	J	1.24E+03	Campbell and Erban (2017)
Nonrenewable natural resources (N_0)				
6	Net loss of topsoil	J	9.40E+04	Brown and Bardi (2001)
Renewable purchased resources (FR)				
7	Manure	g	1.62E+08	Bastianoni et al. (2001)
8	Human labor (10%) *	J	4.83E+05	Lan et al. (1998)
9	Irrigating water	J	5.21E+04	Odum and Arding (1991)
10	Seeds	g	9.07E+08	Coppola et al. (2009)
11	Livestock labor	J	1.85E+05	Lan et al. (1998)
Nonrenewable purchased resources (FN)				
12	Compound fertilizer	g	3.56E+09	Odum (1996)
13	Nitrogen fertilizer	g	4.83E+09	Odum (1996)
14	Phosphate fertilizer	g	4.95E+09	Odum (1996)
15	Potash fertilizer	g	1.40E+09	Odum (1996)
16	Capital investment	¥	9.23E+11	Yang et al. (2010)
17	Human labor (90%) *	J	4.83E+05	Lan et al. (1998)
18	Diesel	J	8.38E+04	Odum (1996)
19	Plastic film	g	4.83E+08	Odum (1996)
20	Pesticides	g	1.10E+10	Brown and Arding (1991)

Note: * Ten percent of human labor was considered as being supported by renewable input and classified as FR, while the left ninety percent was assumed as nonrenewable and classified as FN according to previous studies (Asgharipour et al., 2019; Yang et al., 2010).

Mongolia, Liaoning, Jilin, Heilongjiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Ningxia and Xinjiang (Fig. 2b). Indeed, data of only 17 Chinese provinces (Fig. 2c and d, Table 3) with both industries at the same time were used when two cucumber production systems under different planting patterns were compared with each other.

As shown in Fig. 2a and b, the natural resources (NR) used by both the protected cucumber production system (PC) and the field cucumber production system (FC) were inequably distributed across the country. Overall, the natural resources used by the PC were increasing from south to north, ranging from 3.53E+14 sej/ha in Henan to 8.27E+14 sej/ha in Jilin. However, the natural resources used by the FC had the opposite trend, ranging from 7.84E+14 sej/ha in Xinjiang to 34.77E+14 sej/ha in Yunnan. Moreover, difference between natural resources of the PC and the FC were also inequably distributed in these 17 Chinese provinces and the value was decreasing from south to north (Fig. 2c). In addition, the mean value of NR input (13.59E+14 sej/ha) of the FC was significantly higher than that of the PC (5.92E+14 sej/ha) (Table 3). However, the mean values of the purchased resources (PR), total emergy input (U) and total energy output (Y) had the opposite trend (Table 3). In other words, the mean values of PR, U and Y of the PC (181.91E+14 sej/ha, 187.83E+14 sej/ha and 6.05E+10 J/ha, respectively) were higher than that of the FC (109.42E+14 sej/ha, 123.01E+14 sej/ha and 4.61E+10 J/ha, respectively). What's more, the value of PR input was significantly greater than NR input whether in the PC or the FC (Table 3).

Among the four emergy inputs, the FN had the largest proportion (70.18%), followed by FR (26.50%), then N_0 (3.25%), and finally R (0.08%) in the PC (Fig. 3). The proportion of each input of the FC was slightly different. The FN had the largest proportion (64.93%), followed by FR (23.69%), then R (6.58%), and finally N_0 (4.80%) (Fig. 3). For a detailed analysis, the emergy inputs of human labor, manure, capital investment, compound fertilizer and nitrogen fertilizer accounted for a higher proportion among all emergy inputs (Fig. 3).

The proportion of all resources inputs in the two production systems was comparatively similar, but the numerical difference of these resources inputs was relatively large. As shown in Fig. 4, the emergy inputs of purchased resources of the PC were all more than that of the FC regardless of whether the resources were renewable or nonrenewable. In particular, the emergy inputs of human labor, capital investment, compound fertilizer, pesticides, diesel, plastic film and manure of the PC were significantly higher than those of the FC.

3.2. Comparison of emergy-based indicators between the protected cucumber production system and the field cucumber production system

Table 4 shows a set of emergy-based indicators of the cucumber production systems, making it easy to evaluate the operation of the systems. The emergy self-sufficiency ratio (ESR) is a measure of how many free natural resources are used by the production system (Table 2). Higher value means greater dependence on the environment. The PC had a lower ESR (0.03) than the FC (0.11) (Table 4). In addition, the difference of ESR between the PC and the FC was different in geographical distribution (Fig. 2d). The difference of ESR between the PC and the FC was increasing from north to south. Similar to the indicator ESR, emergy renewability (%R) is an indicator measuring how many renewable resources are used by the production system (Table 2). Higher value means more contribution the renewable resources make to the production system. The %R of the PC (0.27) was also lower than that of the FC (0.30) (Table 4). The emergy yield ratio (EYR) had the same trend, and it is a measure of the production efficiency of a system or process using purchased input to exploit local resources (Tables 2 and 4). The emergy investment ratio (EIR) is the ratio of purchased input to free local input. The EIR of the PC (32.61) was obviously higher than that of the FC (8.64) (Table 4).

The environmental loading ratio (ELR) is a measure of the potential pressure of the given system on the environment (Table 2). Higher value means greater load on the environment. The ELR of the PC (1319.71) was significantly higher than that of the FC (18.42) (Table 4). Meanwhile, the ELR had certain regularity in geographical distribution. The ELR was getting larger from south to north,

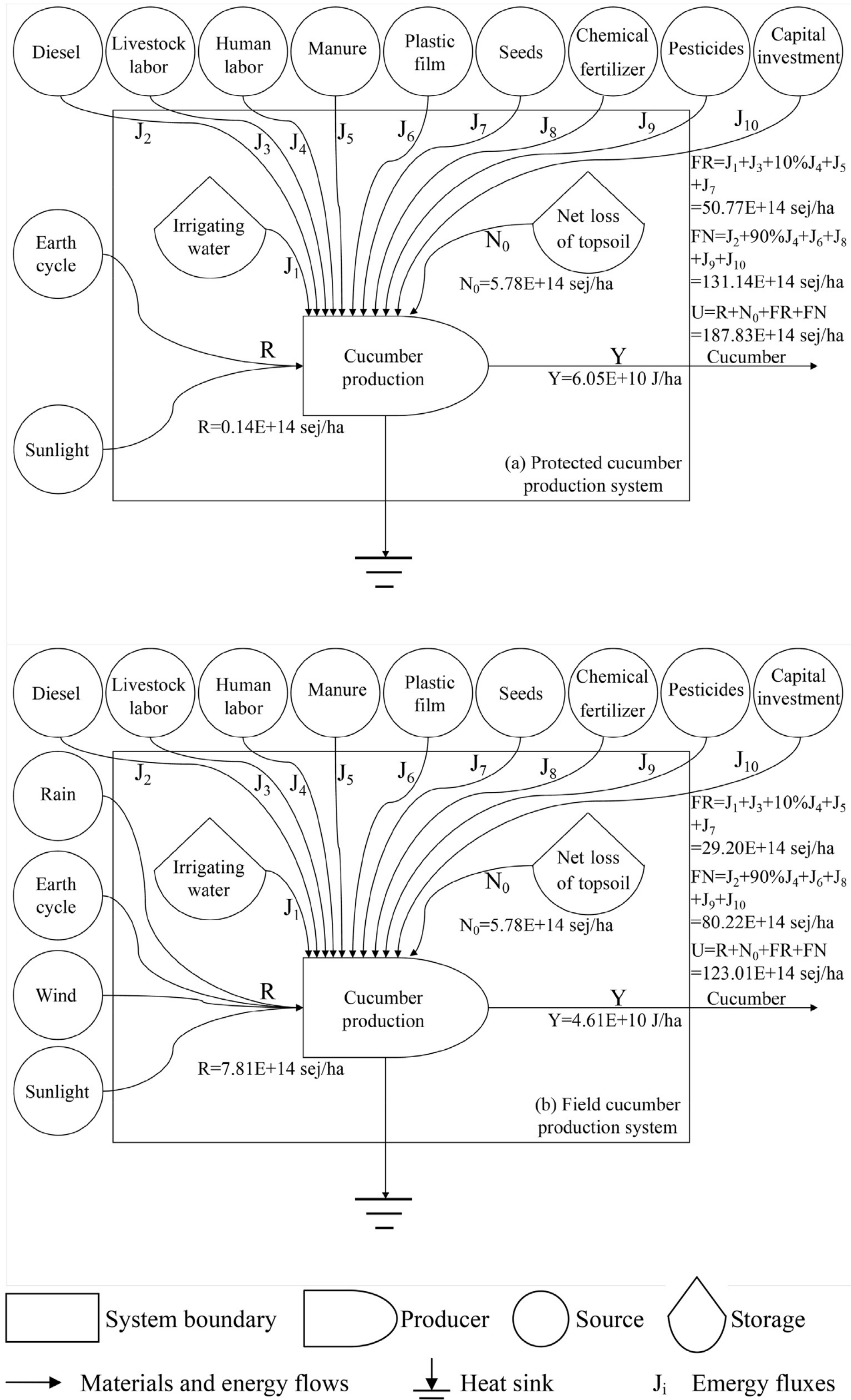

Fig. 1. Energy flow schematic diagrams of the cucumber production systems under different patterns.

Table 2
Emergy indices used to compare the protected cucumber production system and the field cucumber production system.

Index	Symbol	Meaning
Renewable natural resources	R	Emergy of renewable flows directly from local resources such as sunlight
Nonrenewable natural resources	N_0	Nonrenewable or slow-renewable resources used in a nonrenewable manner
Nonrenewable purchased resources	FN	Nonrenewable emergy flows from purchased resources
Renewable purchased resources	FR	Renewable emergy flows from purchased resources
Natual resources	$NR = R + N_0$	Emergy flows directly from natural resources
Purchased resources	$PR=FN + FR$	Emergy flows from purchased input
Total emergy input	$U = R + N_0+FN + FR$	Emergy flows from total input
Total energy output	Y	Total energy of products
Emergy yield ratio	$EYR = U/PR$	A measure of the production efficiency of a system or process using purchased input to exploit local resources
Emergy investment ratio	$EIR = PR/NR$	The ratio of purchased input to free local input
Emergy self-sufficiency ratio	$ESR = NR/U$	A measure of the degree of dependence on the environment
Emergy renewability	$\%R=(R + FR)/U$	A measure of the contribution of renewable resources to the production system
Environmental loading ratio	$ELR=(PR + N_0)/R$	A measure of the potential pressure of the given system on the environment
Transformity	$TRA = U/Y$	A measure of emergy efficiency of the given system
Emergy sustainability index	$ESI = EYR/ELR$	An indicator of system sustainability

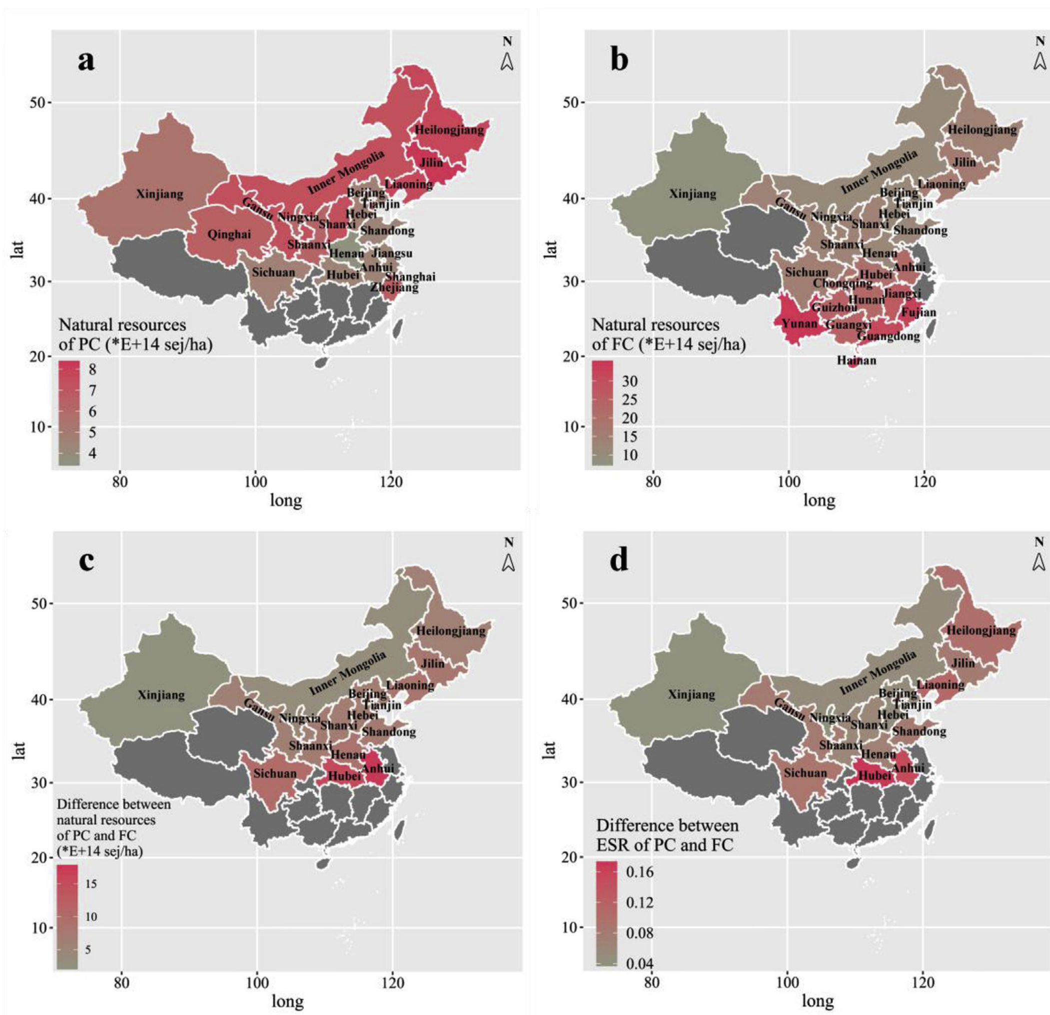

Fig. 2. Comparison of natural resources between the protected cucumber production system (PC) and the field cucumber production system (FC).

especially the ELR of the FC (Fig. 5). The emergy sustainability index (ESI) is a comprehensive indicator reflecting the sustainability of the production system (Table 2). Higher value means that the system has a higher level of sustainability. Contrary to the ELR, the ESI of the PC (0.0008) was extremely lower than that of the FC (0.08) (Table 4). Similar to the ELR, the ESI also had certain regularity in geographical distribution. However, unlike the ELR, the ESI was getting smaller from south to north (Fig. 6). And the ESI of the FC showed more obvious regularity. Transformity (TRA) is the ratio of the total emergy input to the total energy output (Table 2). Lower

Table 3
Comparison of emergy input and energy output between the protected cucumber production system (PC) and the field cucumber production system (FC).

Provinces	NR (*E+14 sej/ha)		PR (*E+14 sej/ha)		U (*E+14 sej/ha)		Y (*E+10 J/ha)	
	PC	FC	PC	FC	PC	FC	PC	FC
Beijing	4.97	12.04	172.19	112.19	177.16	124.24	5.73	5.78
Tianjin	6.32	12.98	111.91	98.89	118.23	111.87	4.67	4.54
Hebei	4.68	11.06	240.78	139.74	245.46	150.80	6.78	5.36
Shanxi	7.31	13.90	228.66	135.97	235.97	149.86	5.75	4.24
Inner Mongolia	7.32	10.65	185.90	106.50	193.22	117.15	5.63	4.97
Liaoning	7.66	15.77	241.23	97.05	248.88	112.82	7.59	3.81
Jilin	8.27	16.12	165.58	112.17	173.85	128.29	5.15	3.54
Heilongjiang	7.69	13.72	149.22	79.34	156.91	93.06	5.76	3.82
Anhui	4.43	21.92	162.35	99.37	166.78	121.30	4.93	3.76
Shandong	4.37	11.42	232.05	100.58	236.42	112.00	7.69	4.73
Henan	3.53	12.00	213.01	121.24	216.54	133.24	5.79	4.51
Hubei	4.37	19.79	97.74	74.32	102.11	94.11	4.46	3.85
Sichuan	4.68	14.61	126.18	104.94	130.86	119.55	6.62	3.65
Shaanxi	6.31	13.01	173.10	130.32	179.41	143.33	5.01	3.67
Gansu	7.32	13.32	208.79	103.95	216.11	117.27	7.88	6.47
Ningxia	5.97	10.81	157.28	129.92	163.24	140.73	6.00	4.63
Xinjiang	5.48	7.84	226.48	113.69	231.95	121.54	7.34	7.01
Mean	5.92	13.59	181.91	109.42	187.83	123.01	6.05	4.61

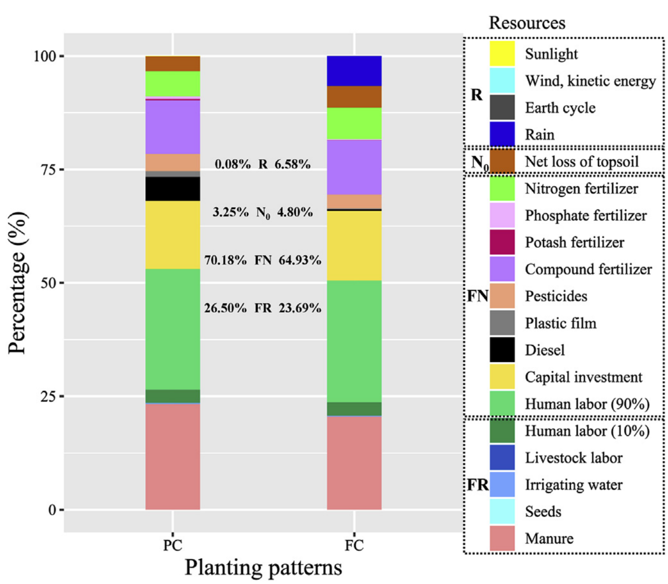

Fig. 3. The proportion of different resources input of the protected cucumber production system (PC) and the field cucumber production system (FC).

value means that the production system yields more energy per unit input of emergy and has higher production efficiency. The TRA of the PC (3.11E+4 sej/J) was significantly higher than that of the FC (2.77E+4 sej/J) (Table 4).

4. Discussion

4.1. Comparison of emergy composition between the protected cucumber production system and the field cucumber production system

Cucumber is an important vegetable, which provides essential minerals, vitamins and nutrients for human body and is the best resource to overcome micronutrient deficiency (Ayyogari et al., 2014). Meanwhile, cucumber is widely planted in China on account of its delicious taste, short nutritional cycle and high economic benefits (Bao et al., 2016). Agricultural production systems including cucumber production systems are highly dependent on climate resources and quite sensitive to climatic and environmental changes. Climate factors and natural conditions affect the potential productivity of agriculture (Cui et al., 2016; Lobell and Burke, 2010).

Natural resources are unevenly distributed in the north and south of China, and the resources available to the cucumber production systems are heterogeneous, so the composition of the materials required for the operation of the systems is different. In general, the low latitude south has better hydrothermal conditions than the high latitude north, especially in the precipitation resources (MWR, 2017). The FC was a relatively open traditional agricultural production system, which made full use of precipitation resources, and the precipitation resources accounted for a large proportion of the natural resources it utilized (Fig. 3). Therefore, the NR of the FC had a decreasing trend from south to north (Fig. 2b). Unlike the FC, the PC was a closed or semi-closed system, which made little use of precipitation resources, and the topsoil accounted for the majority of the natural resources it used (Fig. 3). Moreover, there is no obvious geographical distribution of soil fertility in China, except that the Northeast has the most fertile black soil (Han and Zou, 2018). Consequently, there was little difference in the NR of the PC between regions, except for the NR of Northeast China (Fig. 2a). Comparing the extent to which these two systems used natural resources, the difference between the NR of the PC and the FC and the difference between the ESR of the PC and the FC both showed a decreasing trend from south to north (Fig. 2c and d). These illustrate that the FC used more natural resources and was more dependent on natural resources than the PC. At the same time, in the south of China, where the hydrothermal conditions were better, the gap in the utilization of natural resources was more obvious.

The normal functioning of a production system requires the interaction of natural input and purchased input. The lack of natural input requires more purchased input. Thus, the PR of the PC was much higher than that of the FC, both in numerical value (Table 3 and Fig. 4) and in percentage (Fig. 3). What's more, the FN input made the greatest contribution to the total input in both systems, followed by the FR and then the NR (Fig. 3). In the FN input, the human labor, capital investment, compound fertilizer, nitrogen fertilizer, diesel and pesticides accounted for the majority (Fig. 3). The PR input of both systems accounted for more than 85% of the entire input (Fig. 3), indicating that these two systems were both human-controlled systems highly dependent on artificial investment and interference.

4.2. Comprehensive evaluation of the cucumber production systems and suggestions for sustainable development

The ESR of the PC was significantly lower than that of the FC, and the EIR just had the opposite trend (Table 4). However, these all reflect that the PC is less dependent on the environment than the FC, and has a higher level of economic development (Lan et al., 2002). These results are similar to those of previous studies (Table 5). The protected vegetable system (Wu et al., 2013) and the protected peach system (Wei et al., 2009) have higher EIR (69.96 and 98.83) and lower ESR (0.01 and 0.01), while the field fodder maize system (Ghaley et al., 2018) and the field paddy system (Yi and Xiang, 2016) have lower EIR (4.14 and 11.85) and higher ESR (0.19 and 0.08).

The ELR of the PC (1319.71) was almost 100 times the ELR of the FC (18.42) (Table 4), indicating that the PC had a greater load on the environment than the FC and the two systems were both extremely stressful to the environment with ELRs higher than 10 (Cheng et al.,

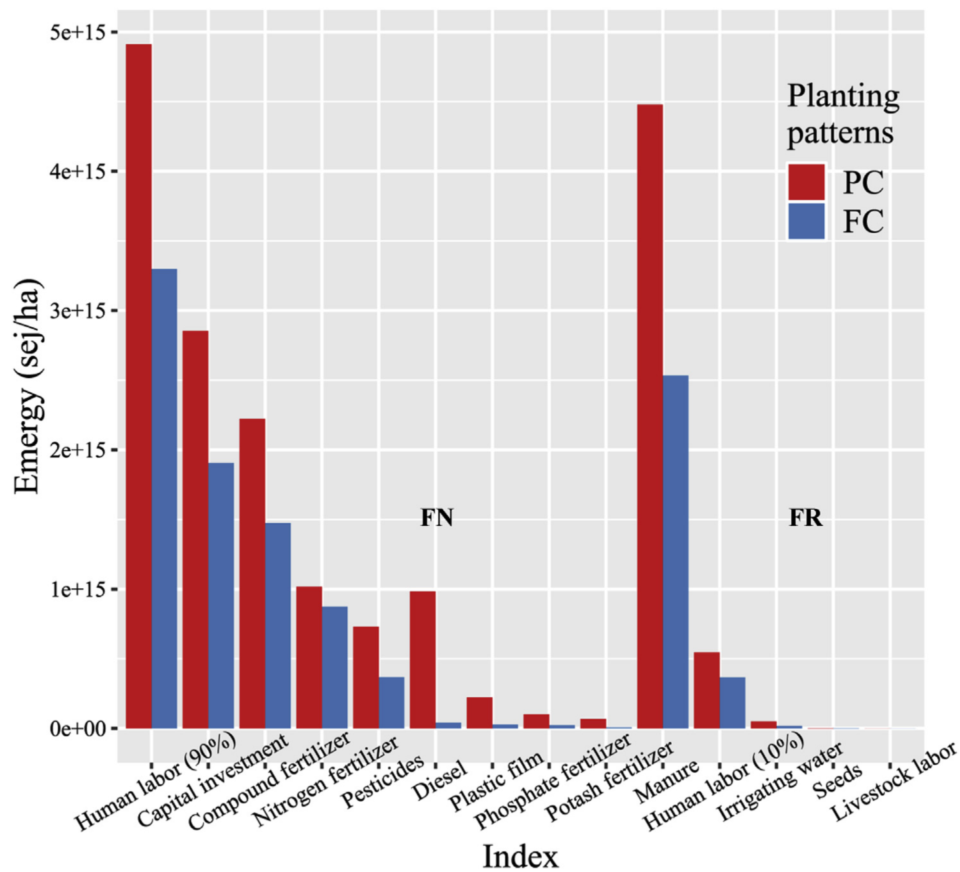

Fig. 4. Emergy of purchased resources input of the protected cucumber production system (PC) and the field cucumber production system (FC).

Table 4
Emergy indices comparison between the protected cucumber production system (PC) and the field cucumber production system (FC).

Planting patterns	EYR	EIR	ELR	ESR	%R	ESI	TRA (*E+4 sej/J)
PC	1.03	32.61	1319.71	0.03	0.27	0.0008	3.11
FC	1.13	8.64	18.42	0.11	0.30	0.08	2.77

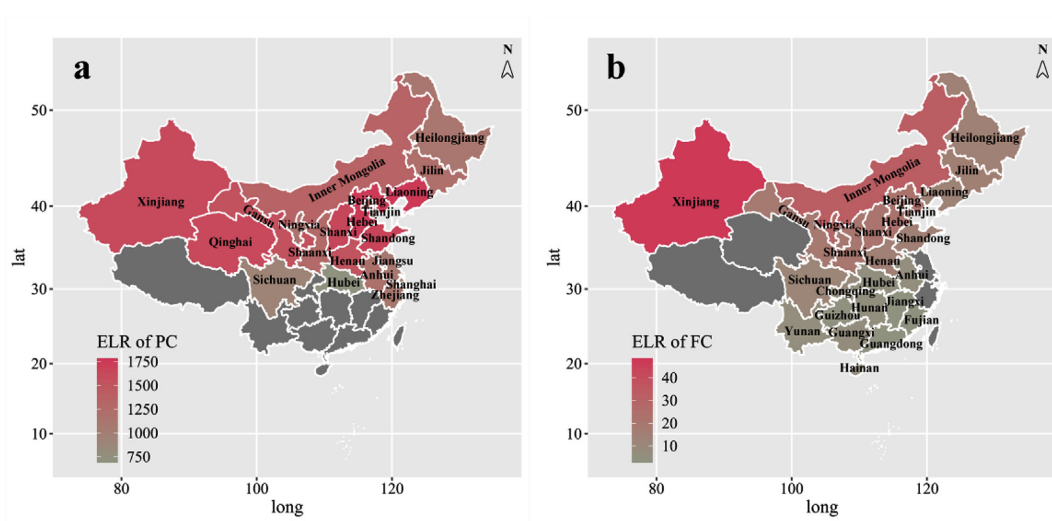

Fig. 5. Comparison of ELR between the protected cucumber production system (PC) and the field cucumber production system (FC).

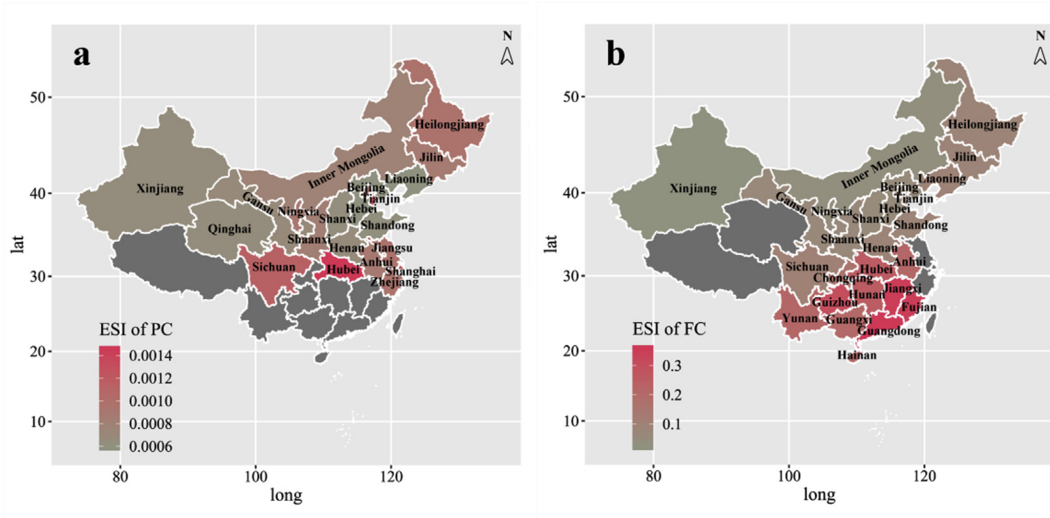

Fig. 6. Comparison of ESI between the protected cucumber production system (PC) and the field cucumber production system (FC).

Table 5
Emergy-based indicators of other agricultural systems.

Systems	EYR	EIR	ELR	ESR	%R	ESI
Protected agricultural systems						
Vegetable (Wu et al., 2013)	1.01	69.96 *	304.19 *	0.01 *	0.20 *	0.0033 *
Grape (Feng et al., 2015)	1.02	51.33	61.71 *	0.02 *	0.19 *	0.0165 *
Peach (Wei et al., 2009)	1.01 *	98.83 *	106.56 *	0.01 *	0.68	0.0095 *
Field agricultural systems						
Vegetable (Lu et al., 2010)	1.05	19.01 *	19.87 *	0.05 *	0.15 *	0.05 *
Cabbage (Zhai et al., 2017)	1.05 *	19.03	21.25	0.05	0.53 *	0.05
Fodder maize (Ghaley et al., 2018)	1.24 *	4.14 *	5.20	0.19 *		0.24
Banana (de Barros et al., 2009)	1.03 *	16.96	17.13	0.04 *		0.06
Paddy (Yi and Xiang, 2016)	2.73	11.85 *	0.77	0.08 *		3.53

Note: * Calculated according to the original data in the paper.

2017). Other protected agricultural systems (Table 5), such as the protected vegetable system (304.19) (Wu et al., 2013) and the protected grape system (61.71) (Feng et al., 2015), also exhibit greater pressure on the environment than other field agricultural systems, such as the field vegetable system (19.87) (Lu et al., 2010) and the field banana system (17.13) (de Barros et al., 2009). The ESI is a comprehensive indicator measuring the system's holistic sustainability in terms of both environmental stress and economic benefit. A higher ESI is the goal that the system must pursue for sustainable development (Zhong et al., 2018). Contrary to the ELR, the ESI of the PC (0.0008) was one hundredth of the ESI of the FC (0.08), indicating that the PC had a lower level of sustainability compared with the FC and the two systems both performed poorly in terms of sustainable production. Similar to the ELR, other protected agricultural systems (Table 5), such as the protected vegetable system (0.0033) (Wu et al., 2013) and the protected peach system (0.0095) (Wei et al., 2009), also exhibit a higher level of sustainability than other field agricultural systems (Table 5), such as the field cabbage system (0.05) (Zhai et al., 2017) and the field paddy system (3.53) (Yi and Xiang, 2016).

The TRA is an indicator measuring the output-input efficiency of the given production system. The higher the TRA, the lower production efficiency. In fact, the U, Y and TRA of the PC were all higher than those of the FC. Therefore, the PC was a high-input, high-output, but inefficient production system compared with the FC. What's more, as mentioned earlier, the PC also used more nonrenewable resources and more artificial resources, and had a greater environmental burden. In general, the PC is an unsustainable and inefficient production system, which we need to pay attention to. The cucumber production system is a typical technology, capital and labor-intensive highly human-controlled system, especially the PC (Bolandnazar et al., 2014). The excessive use of human labor, capital investment, compound fertilizer, nitrogen fertilizer, diesel and pesticides results in high environmental load and low sustainability of the system (Gruda et al., 2019; Liang et al., 2019; Taki and Yildizhan, 2018). It is a good countermeasure to improve the utilization efficiency of resources, for example, to prevent the overuse of chemical fertilizers and improve the absorption rate of chemical fertilizers through soil testing, fertilizer recommendation and precise fertilization (Liang et al., 2019). At the same time, using more clean energy in production process, for example, using renewable energy such as solar energy and wind energy to replace nonrenewable energy such as fossil fuels, will also help to reduce the environmental load on the production system (Gruda et al., 2019; Taki and Yildizhan, 2018). In addition, the use of more and more advanced machinery to replace the labor force and the improvement of the capacity of producers to apply the available technology will also help to improve the efficiency and sustainability of the production system (Bolandnazar et al., 2014).

5. Conclusions

Cucumber is widely cultivated in China, and can be divided into two planting patterns. The extent to which the cucumber production systems under two planting patterns are dependent on the environment is different. The FC is more dependent on the environment and has higher NR input and ESR value. The NR input of the FC (13.59E+14 sej/ha) is more than twice that of the PC (5.92E+14 sej/ha) and the ESR of the FC (0.11) is almost four times that of the PC (0.03). Moreover, the degree of utilization of natural resources by the FC is geographically distributed, and the NR input of the FC has a decreasing trend from south to north. However, the PC uses more purchased resources, especially the nonrenewable purchased resources, which mainly include human labor, capital investment, compound fertilizer, nitrogen fertilizer, diesel and pesticides. And the PR input of the PC (181.91E+14 sej/ha) is almost twice that of the FC (109.42E+14 sej/ha).

The cucumber production system is a typical technology, capital and labor-intensive highly human-controlled system, especially the PC. It has the characteristics of high input, high output but low production efficiency, and has high U, high Y and high TRA. And it also has high ELR and low ESI, which shows the characteristics of heavy environmental load and poor sustainability. In addition to improving the efficiency of resource utilization, more use of clean energy will help alleviate the damage to the environment. At the same time, improving the degree of mechanization and liberating the human labor will also contribute to a more efficient and sustainable development of the cucumber production system.

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