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Emergy Assessment of a Wheat-Maize Rotation System with Different Water Assignments in the North China Plain

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Abstract Sustainable water use is seriously compromised in the North China Plain (NCP) due to the huge water requirements of agriculture, the largest use of water resources. An integrated approach which combines the ecosystem model with emergy analysis is presented to determine the optimum quantity of irrigation for sustainable development in irrigated cropping systems. Since the traditional emergy method pays little attention to the dynamic interaction among components of the ecological system and dynamic emergy accounting is in its infancy, it is hard to evaluate the cropping system in hypothetical situations or in response to specific changes. In order to solve this problem, an ecosystem model (Vegetation Interface Processes (VIP) model) is introduced for emergy analysis to describe the production processes. Some raw data, collected by investigating or observing in conventional emergy analysis, may be calculated by the VIP model in the new approach. To demonstrate the advantage of this new approach, we use it to assess the wheat-maize rotation cropping system at different irrigation levels and derive the optimum quantity of irrigation according to the index of ecosystem sustainable development in NCP. The results show, the optimum quantity of irrigation in this region should be 240–330 mm per year in the wheat system and no irrigation in the maize system, because with this quantity of irrigation the rotation crop system reveals: best efficiency in energy transformation (transformity = 6.05E + 4 sej/J); highest sustainability (renewability = 25%); lowest environmental impact (environmental loading ratio = 3.5) and the greatest sustainability index (Emergy Sustainability Index = 0.47) compared with the system in other irrigation amounts. This study demonstrates that application of the new approach is broader than the conventional emergy analysis and the new approach is helpful in optimizing resources allocation, resource-savings and maintaining agricultural sustainability.

Keywords Emergy analysis · Groundwater · Irrigation · VIP model · North China Plain

Introduction

The sustainability of agricultural development in China is in serious crisis because of the striking conflict between its huge population and limited natural resources such as water and arable land. During the last three decades, with the changes in cropping systems, the increased crop yield in China was achieved at the cost of a large percentage of non-renewable resources consumption and environmental degradation (Yang and others 2006). The adverse environmental consequences of crop production such as soil erosion and water table decline are increasingly serious in China, especially in the North China Plain (NCP). To achieve sustainability of agriculture, it is necessary to evaluate the present cropping system for policy making.

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Because of rapid population growth and irrigation area expansion in NCP, cropping system type had been changed from single-cropping in the 1950s to double-cropping in the 1970s; the winter wheat-summer maize rotation system is the main cropping system at present. Subsequent problems include the dramatic increase in agricultural water demand. Annual water demand for crop production increased from 300 to 400 mm to more than 850 mm (Liu and others 2002), but mean annual precipitation was only 500–700 mm, and it decreased by about 43.9 mm during the past 40 years (Fu and others 2009). Groundwater has become the main irrigation water source and water table decline is the major environmental issue.

The top priority of agricultural management in this area is to resolve the contradiction between high demand and limited water resource availability. A systematic evaluation concentrated on water resources to identify the sustainability of this rotation system is thus required. It is known that the processes of crop production depend highly on the inputs of natural, economic and social resources. Traditional evaluation methods mainly focusing on system productivity are incomplete. A comprehensive analysis tool is needed to identify the impacts of the cropping system on the environment and the economy. For this purpose, the emergy method developed by Odum (1996a, b) is adopted.

Emergy analysis was introduced from Odum in the 1980s (Odum 1988, 1996a, b; Odum and others 2000). It takes the attributions of both nature and humans to generate products and services for an economic-environmental system into consideration, addressing the weakness of traditional energy analysis that fails in its ability to link work potential, environmental support, and wealth generated in the economy (Brown and Ulgiati 1997, 2004). Emergy has been widely used in different systems during the last two decades (Lefory and Rydberg 2003; Tilley and Brown 2006; Yang and others 2003; Lu and others 2006; Higgins 2003). These applications mainly include two types. First are some applied studies which aim to solve special local or process problems, such as ecological systems evaluation with multiple public benefits (Tilley and Swank 2003), estimation of the environmental costs (Cohen and others 2006) and decision making in agriculture production (Cavalett and others 2006; Lefory and Rydberg 2003). These studies provide prime examples that emergy method can be used in different systems to solve local problems. The second type is some theoretical studies for the purpose of using the approach in a more flexible way. A common feature of these researches is that supplements and improvements have been made in emergy methodology. These improvements are mainly in the following three ways. Firstly, quantities of different defined performance indicators are developed to complement the traditional emergy indicators, such as the Emergy Sustainability Index (ESI) which is used to evaluate appropriate non-renewable investments in eco-technology (Brown and Ulgiati 1997); indexes of economic performance, of environmental performance and of sustainable performance which are used to explicitly calculate the emergy required to manage waste flows in an industrial system (Lou and others 2004); Landscape Development Intensity (LDI), which is based on non-renewable emergy use of land uses of a watershed to quantify potential impacts to wetlands (Brown and Vivas 2005). With the help of these new indicators, emergy indicators can provide a more coherent and multidimensional view of the system.

In addition to the development of emergy indicators, some integrations of the emergy approach with other methods are also developed. These modified or integrated emergy methods take advantage of each method, acquire more accurate input data at the regional scale with the help of GIS (Agostinho and others 2008) in emergy analysis and adding emergy accounting in the ecological footprint calculation to get more accurate result (Zhao and others 2005). The aim of this modification is to make the new approach transcend the traditional emergy method and provide an alternative prospect in the study of this area.

Although the second type of theoretical studies mentioned above are useful supplements to the emergy methodology and have strongly promoted its development, the studied system is still in hypothetically steady state. A key issue remains about how to simulate dynamic emergy flow and evaluate system with consideration of the dynamic interactions between components of the ecological system. Dynamic emergy accounting provides a way to solve this issue. Odum (1996a, b) led the way in developing temporally dynamic emergy accounting and Tilley and Brown (2006) advanced it by successfully developing an eco-hydrological model to provide dynamic valuation of a wetland stormwater management system.

However, dynamic emergy accounting is in its infancy, and using it to simulate some complex and critical crop growing process (such as photosynthesis and carbon cycle) still presents difficulties. This difficulty in simulating critical crop-growing processes limits its application in practical decisions made for crop production. In order to solve this problem, in this study, an ecosystem model (VIP (Vegetation Interface Processes) model (Mo and Liu 2001; Mo and others 2004)) which based on radiation, water, heat and CO_2 transfer processes is combined with traditional emergy analysis to describe the dynamic product processes. Therefore, the new ecosystem model-emergy approach can be applied to forecast system performances in different conditions. Furthermore, some practical agronomical activities (such as irrigation amount and fertilizer amount) can be suggested by assessing the system performance in the corresponding conditions.

The objects of this article are (1) to demonstrate how an ecosystem model can be used in emergy analysis to provide assessment of the cropping system with different irrigation amounts, which highlights the interactions between human activities and natural ecosystems and among components of the ecosystem itself, (2) to assess the grain yield and system sustainability of a crop rotation system with irrigation levels and (3) to define an optimum quantity of irrigation under the principle of ecosystem sustainable development and high crop yield.

Methodology

Description of Cropping System

The cropping system under study is a wheat-maize rotation, which represents traditional cropping systems in the North China Plain and accounts for 90% of the cereal sowing area (Chen and others 2008). In this study, we choose a study plot in Shijiazhuang (38°02′ N, 114°25′ E, 81.0 m above sea level), which is located in the northwest of NCP. It has a temperate semi-arid monsoon climate with mean annual precipitation of 475.4 mm. However, the seasonal variation of precipitation is high; about 75% of the rainfall occurs from late June to September during the maize growth stage, and only 25% occurs in the wheat growing period, from October to May. The irrigation demand by winter wheat is about 350–450 mm per year, which is much higher than rainfall in the growing seasons. Due to insufficient rainfall as well as shortage of surface water for irrigation, groundwater is the main irrigation water source in the study area, where groundwater table is about 30 m and recharge rate is 240 mm per year (Chen and others 2006).

Emergy Method

Emergy is defined as the quantity of solar energy directly or indirectly necessary to support a given system (Odum 1996a, b). Since solar energy is the primary source of all kinds of energy on earth, the emergy of all inputs to a system can be expressed on a common basis—solar emergy, which can be calculated by multiplying the energy in Joules (or directly from its mass) by suitable conversion factors called transformities (sej/J). Transformity is a quality factor and gives a measure of the concentration of solar emergy through a hierarchy of process.

The first step of emergy analysis is drawing a diagram of the system to identify all components, their relationships and categories. In this step, available input resources will be developed and allocated to outputs, then all the inputs will be categorized as renewable, non-renewable and purchased. The second step is transforming all the components of a system into emergy by multiplying transformity, which in this study are derived from previous research that has been used to evaluate the energy flows and conversion efficiencies of natural resources, products or service inputs (Odum 1996a, b; Buenfil 2001; Brown and Arding 1991; Cohen and others 2006; Lan and others 2002; Jiang and Chen 2006; Brown and Ulgiati 2004). After all the components of a system are transformed into emergy, some emergy indicators are calculated to assess the system. Hence, solar emergy and transformity, together with other indicators and ratios, are the key elements of emergy analysis, which can be used to evaluate the efficiency and environmental impact of an assessed system, and to make policy recommendations for long-term sustainability.

Approach

Emergy analysis is a quantitative analysis method of an ecosystem. In the analysis, the resources required during the process of developing a product, whether biological resources or commercial products, and the product itself are expressed in a unit of one type of energy. Usually, all the raw data are obtained by investigation or observation. If we want to know the system performances in different situations, we must design different experiments to collect the raw data. The emergy analysis in this study replaces these experiments with an ecosystem model (VIP model), since the ecosystem model is a mathematical representation of an ecosystem and an improvement on theoretical ecology that aims to characterize the major dynamic water use and yield accumulation process of an ecosystem. The advantage of the integrated emergy method is its ability to predict system performance in different situations and in response to particular environmental changes. The steps in application of the integrated emergy method are as follows (Fig. 1), taking the cropping system as an example:

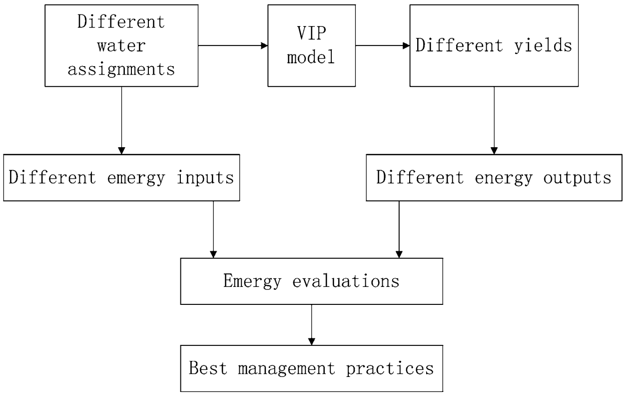


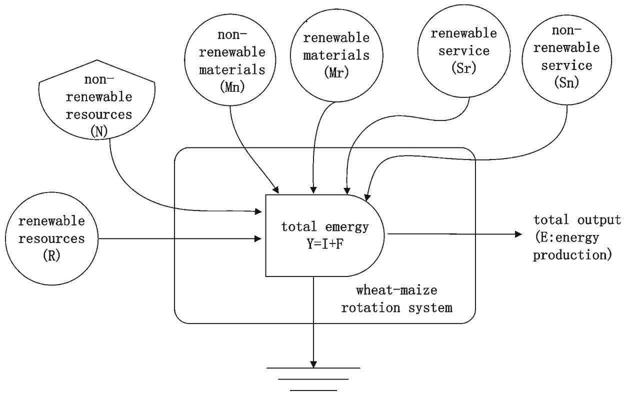
Fig. 1 Framework of ecosystem model-emergy approach

(1) Simulating the system in different situations

The VIP model (detail is shown in next section) is used to calculate the crop yield and evapotranspiration in different irrigation amounts.

(2) Drawing system diagram

Based on the energy circuit diagram described by Odum (1994), an aggregated diagram for the wheat-maize rotation system is presented in Fig. 2 to identify all these components, their relationships and categories. The inputs of the rotation system include rain (evapotranspiration), wind, solar energy, soil loss, groundwater, fertilizers, steel for agriculture machinery, fuel for machinery, chemical inputs, electricity, seed and manpower, and the system output is the crop yield. Unlike the conventional emergy method, evapotranspiration and crop yield are calculated by the VIP model in the first step; the electricity for irrigation is determined by the amount of groundwater pumped up to the ground. Consequently, the emergy values of evapotranspiration, electricity and crop yield alternate with the irrigation amount, by which their emergy values are determined. In these categories, groundwater is a special kind of natural resource and its renewability is hard to determine. Brown and Ulgiati (1997) hold the opinion that a feature of renewable energy is that it is replaced at a rate faster than it is used; without this feature, it should be considered a non-renewable energy. Based on this perspective, groundwater is considered a renewable resource if the use rate stays below its recharge rate of 240 mm per year (Chen and others 2006). If the depletion rate exceeds the recharge rate, the exceeded part is a non-renewable resource and the remainder is still a renewable resource. The classification process of other resources is also presented in Fig. 2. The step (2) combines the VIP model with emergy analysis.



Nature contributions (I) I = R + N

R: rain, wind, solar energy

N: soil loss, groundwater

Feedback from economy (F) F = M + S

Materials (M) M = Mn + Mr

Mn: fertilizers, steel for agriculture machinery, fuel for machinery, chemical, electricity, seed

Mr: none

Services (S) S = Sr +Sn

Sr: none

Sn: manpower

Fig. 2 Emergy system flowchart of wheat-maize rotation system

(3) Evaluating the system

All the inputs and outputs to the system are expressed in an emergy form through their transformities (Table 4 and Appendix). Since the calculation function of all renewable natural resources are coupled with each other, counting each as a separate cost would “double-count” the emergy required for the productive process. The value of total renewable natural resources is equal to its maximum value.

Based on these data, emergy indicators of transformity, renewability, emergy yield ratio, emergy investment ratio, environment loading ratio and environment sustainability ratio (Table 1) are calculated to evaluate system performance and presented in Fig. 4. Their connotations are as follows:

(a) Transformity (Tr): Tr is an indicator to measure how much environmental and economic resources are required to produce one unit of product. The higher the transformity of a product the more resources used to produce it. Therefore, high transformity means high production cost.
(b) Renewability (%R): Renewability is a measure of how much renewable emergy is used by the system. In the long run, a system with a high percentage of renewable resources is more sustainable. It has a larger capability to adapt to environmental pressure and shows greater competitive advantage in comparison with the system using a high percentage of non-renewable resources.
(c) Emergy yield ratio (EYR): EYR is the ratio of the output of emergy divided by the purchased inputs and can be expressed as: EYR $= Y/F$. In this study, $Y = F + I$, EYR can be expressed as: EYR $= (F + I)/F = 1 + I/F$, where F is the purchased inputs and I is the natural resources. So EYR is also an indicator to measure the ability of the production process to exploit local nature resources.
(d) Emergy investment ratio (EIR): EIR is the ratio of purchased input to local natural resources. It is an indicator to measure whether a productive process is a good user of the invested emergy (Brown and Ulgiati 1997). This is not an independent index; it is linked to

Table 1 Emergy indicators

Indicator	Expression	Meaning
Solar transformity (Tr)	Y/E	The ratio of the emergy of the output divided by the energy of the products
Renewability (%R)	100 × (R + Mr + Sr)/Y	The ration of the renewable inputs divided by the total emergy of the system
Emergy yield ratio (EYR)	Y/F	The ratio of total emergy used divided by the emergy of non-renewable inputs from the economy
Emergy invest ratio (EIR)	(Mn + Sn)/(R + Mr + Sr + N)	The ratio of the emergy of non-renewable economic inputs divided by the emergy of nature investment
Environmental loading ratio (ELR)	(N + Mn + Sn)/(R + Mr + Sr)	The ratio of non-renewable emergy and renewable inputs
Emergy Sustainability Index (ESI)	EYR/ELR	Indicates the sustainability of the system

Source: Feni and others 2008; Odum, 1996

EYR and an additional explanation to EYR. A system with low EIR means its productive process uses the invested emergy efficiently.

(e) Environmental loading ratio (ELR): ELR is the ratio of purchased inputs and non-renewable resources to renewable resources. It is an indicator to measure the pressure of the ecosystem.

(f) Emergy Sustainability Index (ESI): ESI was first proposed by Brown and Ulgiati (1997). It is an aggregated measure of yield and environmental loading. It is expressed as: ESI = *EYR*/*ELR*, which shows that a high ESI is provided by a high EYR and a low ELR, so a system with high ESI has good performance both in yield and developmental sustainability.

Description of the Ecosystem Model VIP

The ecological system model used in this study is a dynamic ecosystem model (VIP model) based on radiation, water, heat and CO_2 transfer processes over a relatively uniform field plot. The forcing data are air temperature, water vapor pressure, wind speed, global radiation, sunshine duration and precipitation amount. The main modules are: (1) an improved multi-layer canopy radiative transfer module; (2) a new canopy conductance/photosynthesis module that distinguishes sunlit and shaded leaves; (3) a two-source soil-canopy energy balance module; (4) a multi-layer soil water and heat transfer module (Mo and others 2009; Mo and Liu 2001). The crop yield and evapotransipiration are simulated by the VIP model in this study.

Data Source

Raw Data in Emergy

Most data used in the study were obtained from the Hebei Statistical Yearbook (2001–2007). Evapotranspiration and crop yield were calculated by the VIP model in different irrigation amounts. The input forcing data of the VIP model were obtained from a meteorological station in Shijiazhuang city. Electricity consumption was determined by the irrigation amount (see Appendix).

The irrigation amount used in the study was designed as follows: let W_i be the amount of irrigation water (mm) used in the wheat growing stage and M_j be the amount of irrigation water (mm) used in the maize growing stage, $P = \{\langle W_i, M_j \rangle\}$ was the set of all water assignments in the wheat-maize rotation system, where $W_i \in \{60, 90, 120, \ldots 360\}$, $M_j \in \{0, 30, 60, 90, \ldots 180\}$.

Validation Data for the VIP Model

Field measurement was carried out in a winter wheat field at Luancheng Agricultural Experimental Station during the whole growing season. The station (37°53′ N, 114°41′ E, with elevation at 50.1 m) is located in Shijiazhuang. Winter wheat (Xianyu315) was sowed at the beginning of October 2006 and harvested in mid June 2007. The five irrigation schedules are shown in Table 2 and each treatment was replicated three times. Plant samples were taken once before winter and every 10 days after the recovering green stage by gathering 10–20 stalks to measure the aboveground biomass and leaf area index. The input forcing data of VIP model were recorded at a meteorological station near the winter wheat field.

Numerical Analysis Data

The impact of irrigation on crop yield depends on the particular growth stage of the crop (Singh and others 1991). In order to determine the optimum irrigation period, five irrigation dates (before winter, recovering stage, elongation stage, booting stage, grain filling stage) and three irrigation plans (60, 180, 240 mm) were selected to design the following irrigation experiment in the wheat system. Let $B_{t,w} = \{\langle P_1, P_2, P_3, P_4, P_5 \rangle\}$ be the irrigation assignment

Table 2 Irrigation treatments in wheat system (mm)

Treatments	Before winter	Green return stage	Elongation stage	Booting stage	Grain filling stage
1		80			
2		80		70	
3	70	80		70	
4	70	80	70	70	
5	70	75	70	70	70

plans, t is the times of irrigation, $t \in [1, 5]$. W stands for irrigation amounts (mm), $w \in \{60,180,240\}$. P_i stands for the irrigation amount in the ith irrigation stage, $i \in [1, 5]$, where $i = 1, 2, 3, 4$ and 5 stands for before winter, recovering stage, elongation stage, booting stage and grain filling stage respectively. For all selected irrigation periods, $P_i = w/t$, and for no irrigation periods $P_i = 0$. Due to large size of $B_{t,w}$ sets, we did random sampling of 100 sets in each $B_{t,w}$ except for $B_{1,w}$ and employed the VIP model to simulate the yield of each $B_{t,w}$, then calculated its average yield and coefficient of variation(CV). The same experiment was also conducted in the maize system, the irrigation data were set at the seedling stage, jointing stage and grain filling stage, the irrigation amounts were 60 mm, 120 mm and 180 mm.

Results

Model Validation

The comparisons of simulated and measured biomasses above ground were presented in Fig. 3. Figure 3a presented the aboveground biomass accumulation process in different irrigation treatments. Figure 3b presented the correlation between simulated and measured values. The simulated aboveground biomass was in good agreement with the observations. The correlation coefficient was 0.98 ($R^2 = 0.97$), which demonstrated the reasonability and reliability of the model.

Numerical Analysis

The results of the numerical analysis for emergy were shown in Table 3. The best irrigation assignment was the one with highest average yield and lowest coefficient of variation (CV), which had the highest possibility of obtaining the highest yield. Under this standard, the system $B_{5,w}$ in the wheat system and $B_{3,w}$ in the maize system showed the best performance. Each irrigation amount was divided equally into five irrigation periods in the wheat system and three irrigation periods in maize system.

Emergy Evaluation of the System

Emergy analysis was used to evaluate system performance from 2000 to 2006. Since emergy indicators showed the

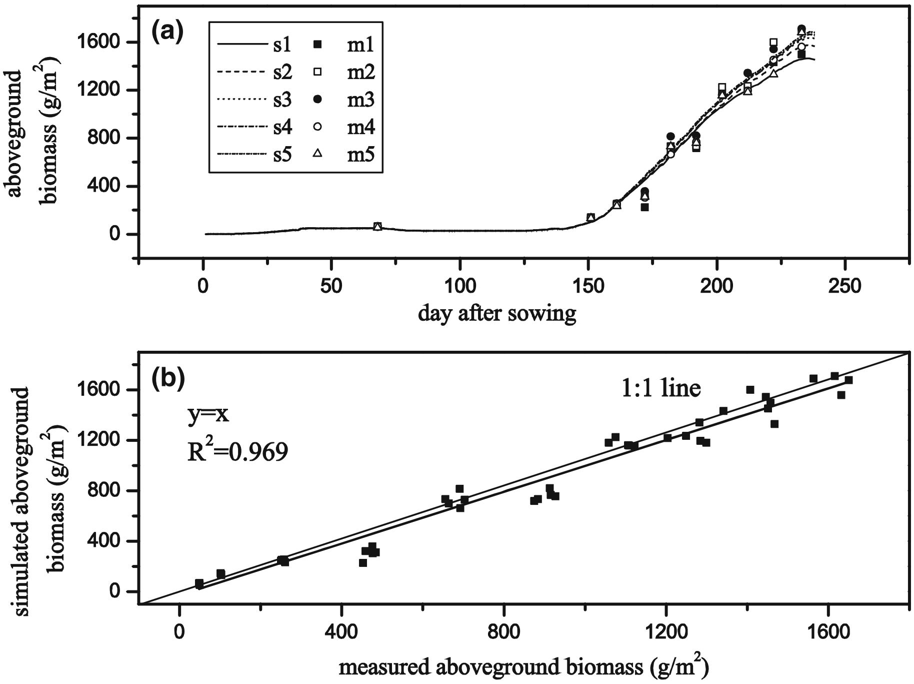


Fig. 3 Comparisons of the simulated and the measured aboveground biomass of winter wheat (**a** The aboveground biomass changing with time; s1, s2, s3, s4, s5: simulated aboveground biomass in treatment1, treatment2, treatment3, treatment4, treatment5 of Table 2; m1, m2, m3, m4, m5: measured aboveground biomass in treatment1, treatment2, treatment3, treatment4, treatment5 of Table 2. **b** Comparisons of simulated and measured aboveground biomass]

Table 3 Crop yield in different irrigation frequency and amount

System style	Irrigation amount	Item	Frequency of irrigation				
			1	2	3	4	5
Wheat	60 mm	Arithmetic mean (kg/ha)	1350	3135	3021	2964	5150
		Standard deviation	16.8	12.37	10.50	9.20	12.11
		Coefficient of variation (%)	1.24	0.39	0.35	0.31	0.23
	180 mm	Arithmetic mean (kg/ha)	4630	5145	5172	5248	5249
		Standard deviation	9.63	20.39	15.16	11.88	8.33
		Coefficient of variation (%)	0.21	0.39	0.29	0.23	0.15
	360 mm	Arithmetic mean (kg/ha)	6807	6302	6626	6754	6810
		Standard deviation	3.15	16.02	8.60	4.84	2.79
		Coefficient of variation (%)	0.05	0.25	0.13	0.07	0.04
Maize	60 mm	Arithmetic mean (kg/ha)	7782	7802	7816	–	–
		Standard deviation	12.37	11.85	10.96	–	–
		Coefficient of variation (%)	0.16	0.15	0.14	–	–
	120 mm	Arithmetic mean (kg/ha)	7888	7931	8023	–	–
		Standard deviation	11.10	10.85	10.79	–	–
		Coefficient of variation (%)	0.14	0.14	0.13	–	–
	180 mm	Arithmetic mean (kg/ha)	8077	8104	8112	–	–
		Standard deviation	10.52	10.12	10.04	–	–
		Coefficient of variation (%)	0.13	0.12	0.12	–	–

same tendency in different years, CVs of emergy indicators in different irrigation amounts were: transformity: 5.8–7.4%; renewability: 0.4–1.1%; emergy yield ratio: 0.8–1.6%; emergy investment ratio: 1.4–2.1%; environmental loading ratio: 1.7–2.8%; Emergy Sustainability Index: 2.5–4.1%. The details of each indicator in 2006 were given below as an example.

Transformity (Tr)

Transformity (Tr) is an indicator to measure how much environmental and economic resources are required to produce one unit of product. The transformities ranged from 6.05E + 4 sej/J to 7.73E + 4 sej/J in different water assignments. Tr revealed a trend of slow increase when irrigation varied from 60 mm to 180 mm for the yield (output) increase slowly (Table 4); as more water resources were put into system (180–240 mm), yield increased quickly (Table 4) and Tr showed a trend of dramatic decrease. Then Tr increased when more than 240 mm of water was provided to the system, because input (non-renewable resource) increased (Table 4). The low transformity was obtained when irrigation varied from 240 to 330 mm (Fig. 4a), which indicated that the product of the system had lowest resources cost under this circumstance. The discrepancy of transformity in the same irrigation amount was due to water allocation in the rotation system and would be explained in section *water allocation*.

Renewability (%R)

Renewability is a measure of how much renewable emergy is used by the system. Since the portion of groundwater which exceeded its recharge rate (240 mm) was considered a non-renewable resource, the highest %R was 25% which was obtained with 240 mm of water supplied (Fig. 4b) as an increase in the amount of irrigation, indicating that the system was more sustainable at this irrigation amount.

Emergy Yield Ratio (EYR)

In this study, the lowest EYR was very close to 1, which indicated little natural resources was exploited in the productive process. As more natural resources were exploited (more groundwater put into system), purchased input (electricity which is used to pump groundwater) increased consequently. The EYR presented a rising trend as more water was put into the system (Fig. 4d), indicating the increased speed of natural resource (groundwater) was higher than that of purchased input (electricity) and electricity was a key factor for exploiting local natural resources. The potential ability of exploiting abundant natural resources during the productive process got stronger as more water was given to the system.

Table 4 Emergy evaluation of wheat-maize rotation system under different irrigation assignments in 2006 (1 ha)

Note	Item	Raw amount	Unit	Transformity (sei/J)	Emergy flow (1E + 14 sej/ha/year)
Renewable resources (R)					
1	Sun	4.19E + 13	J	1	0.42
2	Rain, chemical energy	2.12 ~ 3.95E + 10	J	3.06E + 04	6.50 ~ 12.1
2a	Rain, chemical energy	2.12E + 10	J	3.06E + 04	6.50
2b	Rain, chemical energy	2.67E + 10	J	3.06E + 04	8.16
2c	Rain, chemical energy	3.21E + 10	J	3.06E + 04	9.83
2d	Rain, chemical energy	2.52E + 10	J	3.06E + 04	7.71
2e	Rain, chemical energy	3.06E + 10	J	3.06E + 04	9.37
2f	Rain, chemical energy	3.56E + 10	J	3.06E + 04	10.90
3	Groundwater (renewable part)	0.30E + 10 ~ 1.19E + 10	J	2.27E + 05	0.92 ~ 3.64
3a	Groundwater (renewable part)	2.96E + 09	J	2.27E + 05	6.73
3b	Groundwater (renewable part)	8.89E + 09	J	2.27E + 05	20.20
3c	Groundwater (renewable part)	1.20E + 10	J	2.27E + 05	27.10
3d	Groundwater (renewable part)	7.41E + 09	J	2.27E + 05	16.80
3e	Groundwater (renewable part)	1.20E + 10	J	2.27E + 05	27.10
3f	Groundwater (renewable part)	1.20E + 10	J	2.27E + 05	27.10
Total renewable resources					6.50 ~ 12.1
Non-renewable resources (N)					
4	Soil loss	3.77E + 09	J	1.24E + 05	4.67
5	Groundwater (non-renewable part)	0 ~ 1.48E + 10	J	2.27E + 05	0 ~ 4.53
5a	Groundwater (non-renewable part)	0	J	2.27E + 05	0
5b	Groundwater (non-renewable part)	0	J	2.27E + 05	0
5c	Groundwater (non-renewable part)	2.87E + 09	J	2.27E + 05	6.50
5d	Groundwater (non-renewable part)	0	J	2.27E + 05	0
5e	Groundwater (non-renewable part)	1.38E + 09	J	2.27E + 05	3.14
5f	Groundwater (non-renewable part)	7.31E + 09	J	2.27E + 05	16.60
Total non-renewable resources					4.67 ~ 9.20
Renewable materials (Mr)					
6	Seed	2.22E + 09	J	7.86E + 04	1.75
Non-renewable materials (Mn)					
7	Nitrogen (N)	3.30E + 05	g	6.38E + 09	21.1
8	Phosphate (P_2O_5)	1.02E + 05	g	6.55E + 09	6.68
9	Potash (K_2O)	5.60E + 03	g	1.85E + 09	0.11
10	Compound fertilizer	2.60E + 05	g	2.80E + 09	7.28
11	Fuel for machinery	6.41E + 09	J	1.11E + 05	7.12
12	Pesticide	4.50E + 03	g	2.49E + 10	1.12
13	Steel for agriculture	247.58	$	1.21E + 13	30.0
14	Electricity	2.07E + 08 ~ 1.87E + 09	J	2.77E + 05	0.57 ~ 5.18
14a	Electricity	2.07E + 08	J	2.77E + 05	0.57
14b	Electricity	6.22E + 08	J	2.77E + 05	1.72
14c	Electricity	1.04E + 09	J	2.77E + 05	2.87
14d	Electricity	5.18E + 08	J	2.77E + 05	1.44
14e	Electricity	9.33E + 08	J	2.77E + 05	2.59
14f	Electricity	1.35E + 08	J	2.77E + 05	3.73
Total materials					75.6 ~ 80.2
Renewable services (Sr)					
15	Management and labor	2.31E + 08	J	3.80E + 05	0.88
Total emergy					88.0 ~ 102.0

Table 4 continued

Note	Item	Raw amount	Unit	Transformity (sei/J)	Emergy flow (1E + 14 sej/ha/year)
Total outputs	Wheat	8.77E + 09 ~ 1.01E + 11	J		
	Wheat (a)	8.77E + 09	J		
	Wheat (b)	4.16E + 10	J		
	Wheat (c)	8.65E + 10	J		
	Wheat (d)	1.25E + 10	J		
	Wheat (e)	6.35E + 10	J		
	Wheat (f)	9.43E + 10	J		
	Maize	1.23E + 11 ~ 1.31E + 11	J		
	Maize (a)	1.23E + 11	J		
	Maize (b)	1.26E + 11	J		
	Maize (c)	1.28E + 11	J		
	Maize (d)	1.29E + 11	J		
	Maize (e)	1.29E + 11	J		
	Maize (f)	1.30E + 11	J		

The emergy items (rain, groundwater and electricity) and output in six irrigation treatments were picked out in all treatments to show the emergy variation. These elected treatments were marked a, b, c d, e and f with the irrigation amount 60 mm in wheat system and no irrigation in maize system, 180 mm in wheat system and no irrigation in maize system, 300 mm in wheat system and no irrigation in maize system, 60 mm in wheat system and 90 mm in maize system, 180 mm in wheat system and 90 mm in maize system, 300 mm in wheat system and 90 mm in maize system, respectively

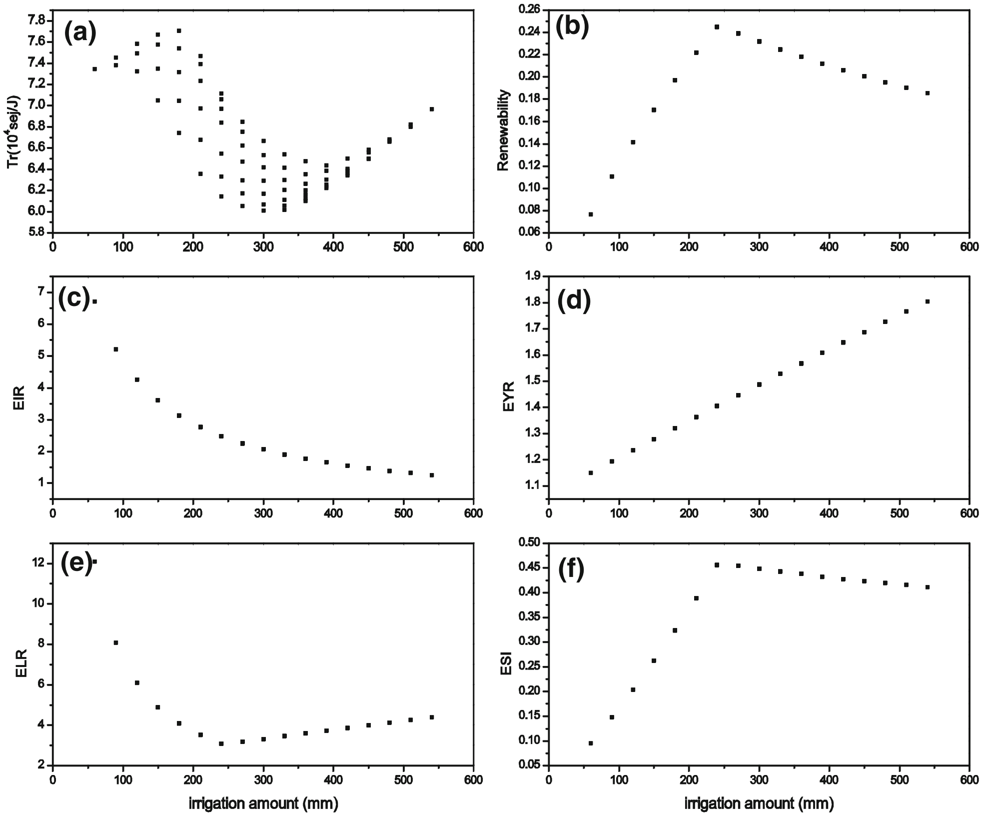


Fig. 4 Emergy indicators of the wheat-maize rotation system in different water assignments (**a** Transformity; **b** Renewability; **c** Emergy investment ratio; **d** Emergy yield ratio; **e** Environmental loading ratio; **f** Emergy Sustainability Index)

Emergy Investment Ratio (EIR)

Emergy investment ratio (EIR) is the ratio of purchased input to local natural resources and an additional explanation to EYR. EIR declined gradually as irrigation rose correspondingly (Fig. 4c). Combining these results with those of EYR demonstrated that the system had a stronger ability to exploit local resources and a higher efficiency in using economic investment as more water was put into the system.

Environmental Loading Ratio (ELR)

Environmental loading ratio (ELR) is the indicator to measure the pressure of the ecosystem. Since groundwater was considered non-renewable resource when exceeded its recharge rate (240 mm), which meant more non-renewable resources were put into system when more than 240 mm water was supplied, the lowest ELR was obtained at the point that 240 mm of water was put into the system while the highest %R was obtained at the same point (Fig. 4e), revealing that the system had the lowest environment pressure at this point.

Emergy Sustainability Index (ESI)

The Emergy Sustainability Index (ESI) is an aggregated measure of yield and environmental loading. Although the system had good performance in EYR as more water was supplied, the ELR didn't show a downtrend when the irrigation amount is more than 240 mm. This meant the increasing yield was at the cost of deteriorating environment if the irrigation amount exceeded 240 mm. So the system had a better performance in ESI when 240 mm water was put into the productive process, as shown in Fig. 4f.

Water Allocation in the Rotation System

The water allocation in the rotation system should be considered in the evaluation, since it leads to differences in the output of yield and transformity. When the irrigation amount was 240 mm, the differences in system output and system's transformity were shown in Fig. 5 as an example.

When the ratio of irrigation in wheat production increased from 25% to 100%, the system's transformity fell from 6.84E + 4 sej/J to 6.05E + 4 sej/J, the output of yield and energy increased from 1.12E + 4 kg/ha to 1.27E + 4 kg/ha and 1.65E + 11 J/ha to 1.88E + 11 J/ha, respectively. In other words, when the irrigation amount stood still in the rotation system, the output of the system increased and the transformity decreased if more water was put into the wheat system. Since transformity provides a measure of emergy efficiency of production (Brown and Ulgiati 2004), these results clearly indicated that with limited water resources, priority should be given to wheat

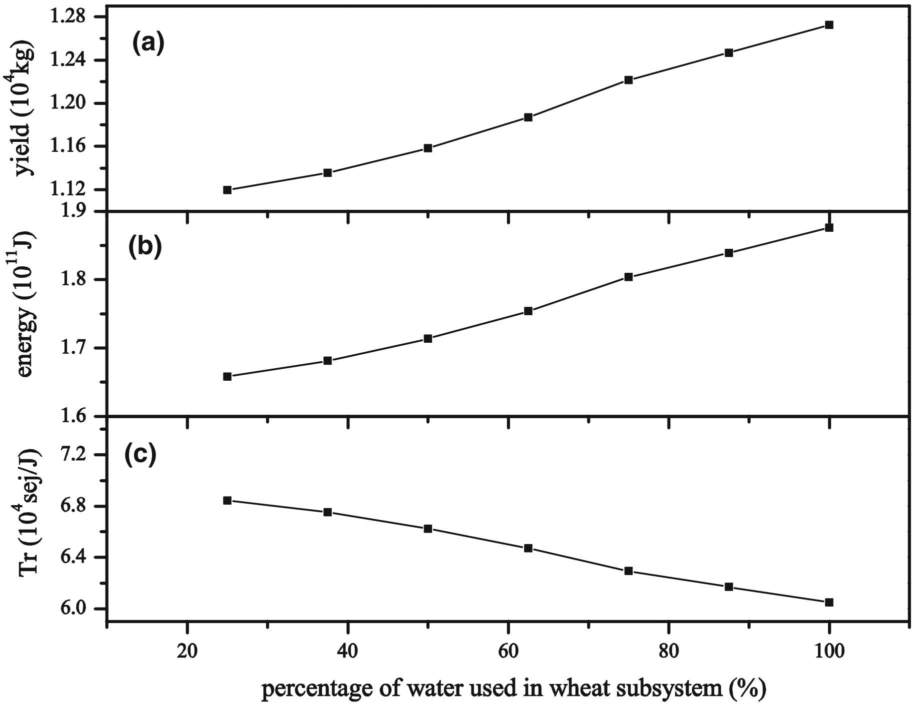


Fig. 5 Dynamic variation of **a** yield, **b** energy and **c** Tr with different water allocations in wheat-maize rotation system

irrigation to achieve higher efficiency in the current rotation system.

Discussion

The Optimum Quantity of Irrigation

The objective of this study is to use the emergy method with the support of an ecological model to optimize the irrigation water assignment for the system. The combination of the two provides a more comprehensive method of assessment as it gives a deep insight into the dynamic interaction among components of the ecosystem.

Groundwater was the primary factor for the differences in the emergy flow and sustainability of the system in different irrigation amounts. Pumping more groundwater increased renewable energy flow and material energy flow by increasing evapotransipiration and electricity consumption, respectively. A problem that came along with these changes was that not all emergy indicators reached their best performances in the same irrigation amount.

When the irrigation amount varied from 240 mm to 330 mm, the system produced good performance in transformity, renewability, environmental loading ratio and Emergy Sustainability Index, nevertheless, the system gave good performance in other indicators, e.g. emergy yield ratio and emergy investment ratio when the maximum amount of water was imported into the system. To determine the optimum quantity of irrigation and explain this phenomenon, formulae for EYR and ELR were devised as follows (Brown and Ulgiati 1997):

$$\begin{aligned}\mathrm{EYR} &= Y/F = (R+N+Sn+Sr+Mn+Mr)/\\ &\quad (Mn+Mr+Sn+Sr)\\ &= 1+R/(Mn+Mr+Sn+Sr)\\ &\quad +N/(Mn+Mr+Sn+Sr)\\ &= 1+\alpha+\beta\end{aligned} \tag{1}$$

where:

$\alpha = R/(Mn+Mr+Sn+Sr)$,

$\beta = N/(Mn+Mr+Sn+Sr)$

In this study, Mr = 0, Sr = 0 (Fig. 2); α and β can be expressed as: $\alpha = R/(Mn+Sn)$, $\beta = N/(Mn+Sn)$, respectively.

$$\begin{aligned}\mathrm{ELR} &= (Mn+Sn+N)/(R+Mr+Sr)\\ &= (Mn+Sn+N)/R\\ &= (Mn+Sn)/R+N/R\\ &= 1/\beta+\alpha/\beta\end{aligned} \tag{2}$$

α and β are the ratios of renewable and non-renewable resources to the purchased inputs which measures how much renewable and non-renewable resources are exploited by the productive process, respectively. When irrigation is less than 240 mm, the consumption rate of groundwater is slower than its recharge rate (240 mm); this part of groundwater is renewable. Therefore, α appeared to increase while β kept steady. When irrigation is more than 240 mm, the use rate of groundwater is faster than its recharge rate; the exceeding part is considered non-renewable. So α remained constant while β appeared to increase (Fig. 6). In the first case, the upward trend of EYR and downward trend of ELR were due to the increase of α; in the second case, the increase of β led to an upward trend of EYR and ELR. These results demonstrated that a high contribution to the social economy was at

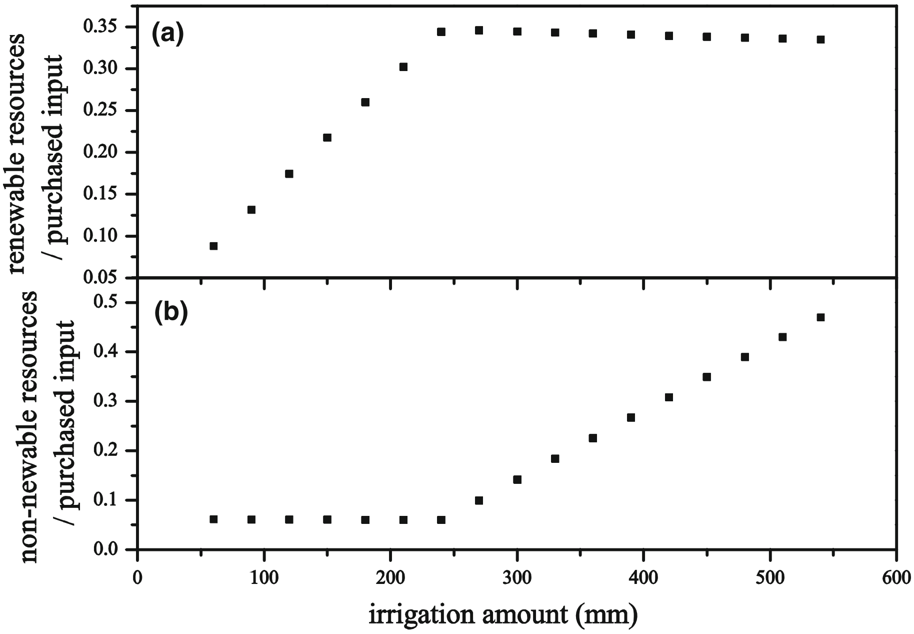


Fig. 6 Dynamic variation of the ratios of **a** renewable and **b** non-renewable nature resources to purchased inputs with different irrigation amounts

the high risk of compromising the environment if more than 240 mm of groundwater was pumped. In the long run, such development of an agricultural system was unacceptable, since environmental damage needed more investment (time and money) to recover. Therefore, interpreted from the strategic implication of emergy indicators, the optimum quantity of irrigation should be 240–330 mm per year in current circumstances.

Water Allocation

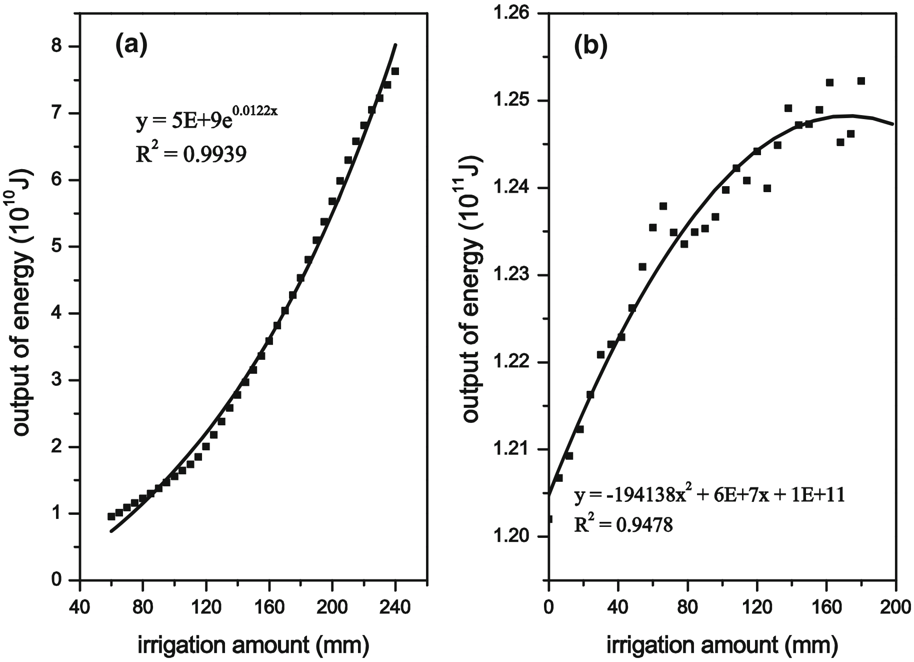
Lotka's Maximum Power Principle is the fundamental basis of Odum's emergy theory. It is explained by Brown and Herendeen (1996) as follows: "systems that will prevail in competition with others develop the most useful work from in-flow emergy sources by reinforcing productive processes and overcoming limitations through system organization." Therefore, an 'optimum performance' is available by adjusting the structure of the system or by redistributing the inputs to the system, and usually this is done by nature (Lotka 1922). This theory was supported in our study by the above gross graphic analysis—different water allocation resulted in different system's outputs and different emergy flows. However, the cropping system was strictly controlled by human activities, and it was humans who determined its development trend. So it was our responsibility to select 'optimum performance' for it. In order to get maximized energy from the productive process, a thorough analysis of each system was necessary and the following experiment was designed to solve this problem.

Wheat yields and maize yields were calculated by the VIP model as their irrigation amounts ranged from 60 to 240 mm and 0 to 180 mm, respectively. The results showed the relationship between energy and irrigation could be described by an exponential function in a wheat system, while in a maize system it was described by a quadratic function, as shown in Fig. 7. When the irrigation amount increased by 180 mm, the corresponding output energy was increased by 6.68E + 10 J in the wheat system and 5.02E + 09 J in the maize system. About 3.71E + 08 J of energy in the wheat system and 2.79E + 07 J of energy in the maize system could be increased by 1 mm of water, respectively. In other words, the wheat system had a higher energy growth rate than the latter. In order to maximize energy output, the limited resources should be used in the system which had a rapid growth rate of energy production. Therefore, 240–330 mm of water should be used to irrigate in wheat system and no irrigation in the maize system, which was in accordance with the conclusion of the graphic analysis.

Suggestions for Further Development

In the wheat system, the optimum quantity of irrigation was 240–330 mm according to the principle of sustainable water use. This result was consistent with the optimum irrigation of 300 mm for the purpose of maximum yield through field experiments (Sun and others 2006) and a little lower than 270–400 mm irrigation demand (Li and others 2007) which was calculated with the Penman-Monteith equation. In the maize system, the optimum quantity of

Fig. 7 Output of energy in different irrigation amount (**a** is the wheat subsystem; **b** is the maize subsystem)



irrigation was 0 mm in this study, which was much lower than 0–300 mm irrigation demands (Li and others 2007). These comparisons revealed that the optimum quantity of irrigation was less than the irrigation demand, and thus suggested the needs of adjusting the existing irrigation schedule as the regional sustainability was also taken into consideration. But with some water-saving irrigation technologies and management, it will be possible to get a high yield in a wheat-maize rotation system with 240–330 mm irrigation.

Emergy indicators under optimum quantity of irrigation were compared with those from the reported studies to give more advice for further development. Grain productivity in the wheat-maize system with transformity of 6.05E + 4 sej/J in this study was more efficient than wheat productivity in Italy and Henan province of China with transformity of 1.59E + 5 sej/J (Ulgiati and others 1994) and 1.32E + 5 sej/J (Dong and others 2008) respectively. Because the maize productivity needed no irrigation, with the same consumption of renewable (water) and non-renewable (electricity) resources, the rotation system could produce more output than the single wheat system. The environmental loading for the rotation system was higher (3.08) than Italian wheat system (2.3) (Ulgiati and others 1994) and lower than Australian lupin-wheat system (5.5) (Lefory and Rydberg 2003). The comparisons with two foreigner wheat systems illustrated that the agricultural technology investments and renewable resources in this region were less than those in other counties. The limited renewable resources not only restricted the sustainable development of the cropping system and rapid economic growth, but also revealed a conflict between the two. Therefore, the optimum quantity of irrigation (240–330 mm) was similar with the recharge rate of groundwater (240 mm) for the sustainable system at the basic of making best use of renewable nature resources. Since society can not achieve sustainable development offset by the cost of endangering the environment, the optimum way is to gain replenishment from nearby regions where resources are plentiful.

Conclusion

In this study, an integrated ecosystem model-emergy approach was proposed and demonstrated. The approach combined the VIP ecosystem model with traditional emergy analysis and had two characteristics. First, it used the VIP model to reveal the dynamic interaction among components of the ecosystem which were constantly ignored in traditional emergy analysis. Second, the approach retained the most attractive characteristics of emergy analysis, which allowed all resources to be expressed in a common unit and compared with on an equal basis; this made it possible to account for both environmental impacts and economic factors in the system evaluation with this approach. Based on this approach, optimum quantity of irrigation in a wheat-maize rotation crop system was estimated. The rotation crop system revealed: good efficiency in energy transformation (transformity = 6.05E + 4 sej/J); high sustainability (renewability = 25%); low environmental impact (environmental loading ratio = 3.5) and a greater sustainability index (ESI = 0.47) compare with the system in other irrigation amounts when irrigation amount was 240–330 mm per year in the wheat system and no irrigation in the maize system. The emergy yield ratio and emergy invest ratio didn't show best performance in that irrigation amount, their development were at the cost of deteriorating environment when irrigation amount exceed 240 mm per year. So the optimum quantity of irrigation should be 240–330 mm per year under the principle of ecosystem sustainable development and high crop yield. With the advantages from the ecosystem model and emergy method, the integrated ecosystem model-emergy approach therefore provided a new method to perform ecosystem analysis in different situations with and without human interferences and had a broader application than conventional emergy analysis.

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Appendix

Calculations and References to Table 4

1 Sun: Mean annual global radiation of 5240 MJ/m^2. Albedo = 20%. Energy received over land = 10000 m^2 $\times$ 5.24 $\times$ 10^9 J/m^2 $\times$ (1–20%) = 4.19 $\times$ 10^{13} J/ha year. Transformity = 1 (Odum 1996a, b).

2 Rain, chemical energy: Precipitation = 349.8 mm, evapotransipiration of crop = 430 ~ 800 mm (calculate by VIP model). Chemical energy of rain over land = 10000 m^2 $\times$ 0.43 ~ 0.8 m (evapotransipiration) $\times$ 1000 kg/m^3 (density of rain) $\times$ 4940 J/kg (Gibbs free energy of rainwater) = 2.12E + 10 ~ 3.95E + 10 J. Transformity from Odum (1996a, b).

3, 5 Groundwater: Annual groundwater consumption = 60 ~ 540 mm. Renewable part is 60 ~ 240 mm, nonrenewable part is 0 ~ 300 mm. Chemical energy of groundwater over land = 10000 m^2 × 0.06 ~ 0.54 m (evapotransipiration) × 1000 kg/m^3 (density of rain) × 4940 J/kg (Gibbs free energy of rainwater) = 0.30E + 10 ~ 2.67E + 10 J. Renewable part is 0.3E + 10 ~ 1.19E + 10 J, nonrenewable part is 0 ~ 1.48E + 10 J. Transformity from Buenfil (2001).

4 Soil loss: Average soil loss = 8.45t/ha (Feng and others 2008), organic matter = 0.01972 kg/kg soil (Wu and Cai 2006). Energy of soil loss = 8.45 × 10^3kg/ha × 0.01972 kg/kg × 5400 kcal/kg (organic matter energy) × 4186 J/kcal = 3.77E + 09 J. Transformity from Brown and Arding (1991).

6 Seed: Annual consumption is 1.40E + 05 g/ha, where 1.20E + 05 g/ha is used in the wheat growing stage and 0.2E + 05 g/ha is used in the maize growing stage (Heibei statistical yearbook, 2007). Energy of seed = 1.20E + 05 g/ha × 1.57E + 04 J/g + 0.2E + 05 g/ha × 1.65 E + 04 J/g = 2.22E + 09 J. Transformity from Cohen and others (2006).

7 Nitrogen: Annual consumption is 3.30E + 05 g/ha, where 1.84E + 05 g/ha is used in the wheat growing stage and 1.46E + 05 g/ha is used in the maize growing stage (Heibei statistical yearbook, 2007). Transformity from Odum (1996a, b).

8 Phosphate: Annual consumption is 1.02E + 05 g/ha, where 0.86E + 05 g/ha is used in the wheat growing stage and 0.16E + 05 g/ha is used in the maize growing stage (Heibei statistical yearbook, 2007). Transformity from Odum (1996a, b).

9 Potash: Annual consumption is 5.60E + 03 g/ha, where 4.88E + 03 g/ha is used in the wheat growing stage and 0.72E + 03 g/ha is used in the maize growing stage (Heibei statistical yearbook, 2007). Transformity from Odum (1996a, b).

10 Compound fertilizer: Annual consumption is 2.60E + 05 g/ha, where 1.68E + 05 g/ha used is in the wheat growing stage and 0.92E + 05 g/ha is used in the maize growing stage (Heibei statistical yearbook, 2007). Transformity from Lan and others (2002).

11 Fuel for machinery: Fuel for machinery = 144 kg/ha (Accessed online November 5, 2009 http://www.hebwj.gov.cn/upfiles/xy_col28super_20061107144551626762.htm). Higher heating value of diesel = 4.45 + E07 J/kg (Boustead and Hancock, 1981). Total energy of diesel fuel = 144 kg/ha × 4.45E + 07 J/kg = 6.41E + 09 J. Transformity from Odum (1996a, b).

12 Pesticide: Annual pesticide is 4.5E + 03 g, where 1.5E + 03 g/ha is used in the wheat growing stage and 3.0E + 03 g/ha is used in the maize growing stage (personal on-field investigation of the authors). Transformity from Brown and Arding (1991).

13 Steel for agriculture: Steel for agriculture is 247.58$, where 166.23$ is used in the wheat growing stage and 81.35$ is used in the maize growing stage. Transformity from Jiang and Chen (2006).

14 Electricity: Amount pumped groundwater (Q) = (0.06 ~ 0.54) m × 10000 m^2 × 1t/m^3 = 600 ~ 5400 t, power consumption rate (e) = 2.72/η (engine efficiency, usually 0.85 for electricity machine) = 3.2, electricity consumption = 3.2 (e) × 0.6 ~ 5.4 kt (Q) × 30 m (groundwater table) × 3.6E + 06 J/kw h = 2.07E + 08 ~ 1.87E + 09 J. Transformity from Brown and Ulgiatil (2004).

15 Management and labor: Annual number of persons for planting, harvesting, driving machines is 13.6, with 6.5 in wheat system and 7.1 in maize system. Daily working time is 8 h and energy consumption is 2.12E + 09 J/h for each person. Total energy = 13.6 × 2.12E + 06 J/h × 8 = 2.31E + 08 J. Transformity from Lan and others (2002).

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