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Article

Understanding Relationships among Agro-Ecosystem Services Based on Emergy Analysis in Luancheng County, North China

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Abstract: Exploring the relationship between different services has become the focus of ecosystem services research in recent years. The agro-ecosystem, which accounts for one-third of the global land area, provides lots of services but also disservices, depending on resources provided by other systems. In this paper, we explored the agro-ecosystem from four aspects: a summary of different indicators in the agro-ecosystem, input and output changes with time, relationships between different ecosystem services and disservices, and resource contribution to major services, using Luancheng County of North China as the study area. We then used emergy analysis to unify all the indicators. The conclusions were that the agro-ecosystem maintained provisioning and regulating services but with increasing volatility under continued growth in production inputs and disservice outputs. There was a positive correlation between most of the different services and disservices. Rainfall and groundwater resources were the most used input resources in the agro-ecosystem and all other major ecosystem services depended directly on them.

Keywords: ecosystem services; ecosystem disservices; emergy analysis; Luancheng County; China

1. Introduction

Ecosystem services, defined as the benefits humans derive from the ecosystem, has become the focus of ecosystem research in recent years [1–5]. The increasing focus on ecosystem services research started from the recognition and monetary valuation of the benefit flows from ecosystems to society, such as mapping supply and demand and assessing the current and future status of ecosystem services [6]. The research has progressed in recent times to the mechanism of providing ecosystem services and management based on different ecosystem services, using different methods [7–12]. While managing multiple ecosystem services simultaneously is important, it is also extremely challenging. Humanity has invested substantial effort into engineering the ecosystem to produce desired services such as food, timber, and fodder but often at the expense of other services of the ecosystem such as flood control, *etc.* Exploring the relationship between different services has become the focus of research in recent years, with the aim of improving our ability to sustainably manage the ecosystem to provide multiple services [13,14].

The agro-ecosystem accounts for one-third of the global land area with high productivity and is dependent on other systems. Extrapolating global trends from 1960 onward, Tilman *et al.* [15] predicted that by 2050, cropland will increase by 23% and pasture land by 16%. Hence, agriculture accounts for a massive and growing share of the Earth's surface. It was proposed that the agro-ecosystem could provide other services, such as provision of clean air, retaining and recycling of nutrients, mitigation against climate change, *etc.*, in addition to food alone when evaluated based on the scope of ecosystem services [16–18]. Although agro-ecosystem services have been assigned relatively low value [19] when compared with other terrestrial and aquatic ecosystems, they offer the best chance of increasing global ecosystem services provision [20]. Porter *et al.* [20] estimated the ecosystem services of a combined food and energy agro-ecosystem that simultaneously produces food, fodder, and bioenergy. Sandhu *et al.* [21] investigated and quantified the value of ecosystem services of the organic and conventional arable system. Both of them tried to improve the agro-ecosystem services. New estimation frameworks or methods have been widely explored to gain a more accurate estimate of services from the agro-ecosystem. Schulte *et al.* [22] provided a framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Robinson *et al.* [23] and Dominati *et al.* [24] also developed their soil frameworks to evaluate ecosystem services. Dominati *et al.* [25] used a soil change-based methodology to quantify and value the services from agro-ecosystems. In addition, Ibarra *et al.* [26] valued the ecosystem services of urban wetlands using an agro-ecosystem approach.

While an agro-ecosystem provides important provisioning services, it also creates disservices and consumes resources from other systems [20,27]. The consumption of water, emissions of greenhouse gases, and discharging of underutilized fertilizer adversely affect human beings. Despite real differences, few studies distinguish among ecosystem services, ecosystem disservices, and resource consumption in their evaluation of an ecosystem. For example, the agro-ecosystem needs water for irrigation, which should be classified as resource consumption, but is often considered as an ecosystem disservice [28–30].

In this study, we first developed a conceptual framework and explored the structures and changes in agro-ecosystem input resources, output services, and disservices, and then analyzed the relationships among different services. Finally, we explored the relationship between input resources and major services, taking Luancheng County (North China) as a case study.

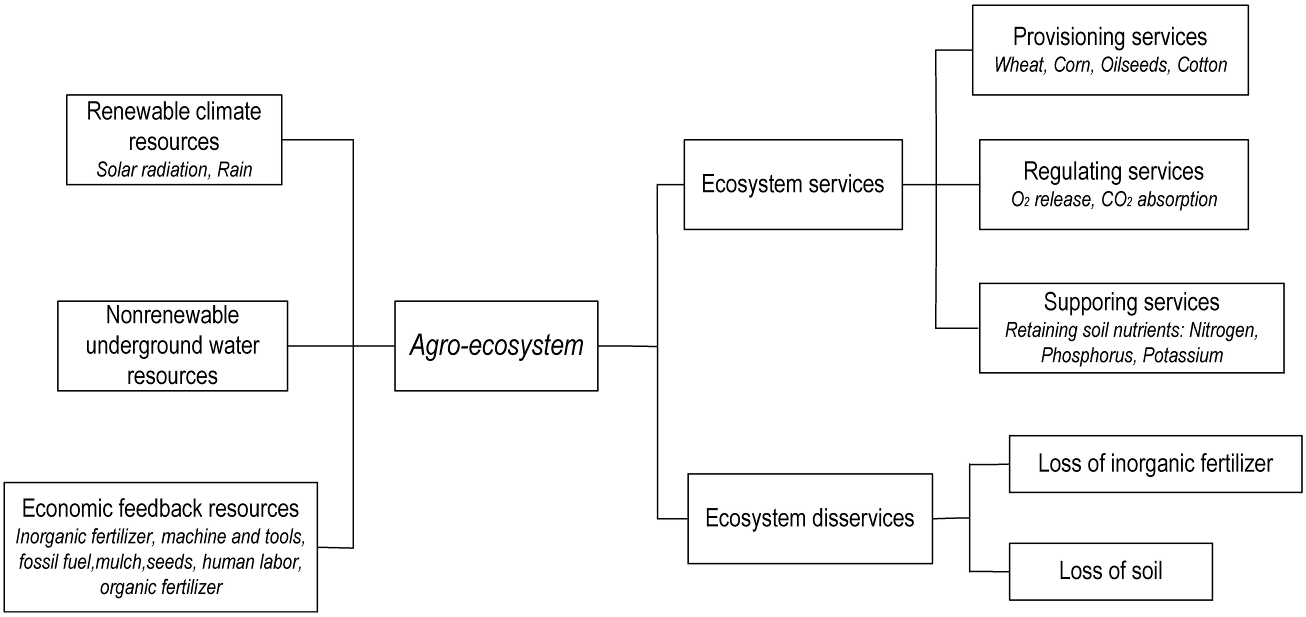
2. Conceptual Framework

Ecosystem services are defined as the benefits people obtain from the ecosystem in the Millennium Ecosystem Assessment (MEA), which is generally consistent with current usage in the literature, although some scientists noted that this definition mixes "ends" and "means" [31–33]. Considering this ambiguity, Boyd and Banzhaf opined that "the final ecosystem services are components of nature, directly enjoyed, consumed, or used to yield human well-being" for developing the national-scale environmental welfare accounting and performance assessment [34]. Fisher and Turner [33,35] considered ecosystem services to be the aspects of the ecosystem utilized (actively or passively) for human well-being. However, ecosystem services are defined differently depending on the research goals [35]. Here, we adopted the definition in MEA, since the focus of our research was not on distinguishing whether the benefits belong to final services or not. "Ecosystem disservices" is another controversial term with different definitions. Zhang *et al.* [27] characterized ecosystem disservices as a reduction in productivity or increase in production costs. Lyytimäki *et al.* [36] considered disservices to be ecosystem functions disturbed by human activities. We define ecosystem disservices as adverse effects on human beings and the ecosystem, considering the resources cost separately in our framework.

Separately measuring the components of ecosystem inputs and outputs adds clarity to ecosystem evaluation and can enhance the recognition of the relationship between the ecosystem and human beings. The ecosystem inputs refer to the resource consumption by the ecosystem while the ecosystem outputs include the ecosystem services and disservices. Since this study focused on the agro-ecosystem, the components of resource inputs include renewable climate resources, the nonrenewable underground water resource, and purchased renewable and nonrenewable resources from human economical feedback. Underground water is separated from renewable resources because the groundwater resource is yearly over-exploited and the recharge rate is much less than the exploitation rate. Groundwater could not therefore be classified under renewable resources. We divided the ecosystem services outputs into provisioning services, regulating services, and supporting services. The ecosystem disservices outputs included the loss of inorganic fertilizer (classified under provisioning disservices) and loss of soil (supporting disservices).

The entire framework for the study is shown in Figure 1. The agro-ecosystem, being our research focus, is located in the middle of the framework. Three inputs—renewable climate resources, the nonrenewable groundwater resource, and economic feedback resources—are arranged to the left side. The ecosystem services and disservices are shown on the right side of the framework.

Figure 1. Conceptual framework for evaluating the agro-ecosystem.



3. Materials and Methods

3.1. Study Area

The North China Plain (NCP) is one of the most productive and intensively cultivated agricultural regions in China. About 50% of the nation's wheat and 33% of its maize are produced in this region. Our study area, Luancheng County, is located in NCP and is a typical high-production agro-ecosystem. It is a traditionally agricultural county. Agriculture accounts for 23.8% of GDP, greater than Hebei Province's ratio of 15%, although Hebei Province is a major grain-producing province in China. The yield of wheat in the area was 7210.5 kg/ha and that of corn was 8730.0 kg/ha in 2005. The yearly government subsidy to farmers is about 4200 Yuan/ha (nearly 700 $/ha), with strict regulations to protect farmland from illegal occupation to ensure national food security.

The area is characterized by a warm temperate continental monsoon climate with an annual mean temperature of 12.7 °C, with the highest temperature (26.4 °C) in July and the lowest (3.9 °C) in January. Mean solar radiation is 724 kJ/(cm^2·a) and the annual sunshine hour is 2521.8 h. Annual precipitation is about 536 mm, 2/3 of which is concentrated in summer. The geomorphology is piedmont alluvial plain and topography is flat with meadow cinnamon soil type. The groundwater resource is abundant with salinity of 0.5–1.0 g/L and the water table is shallow. However, the water table has continued to decline in successive years due to severe overexploitation for irrigation. The contradiction between water scarcity and irrigation of the agro-ecosystem has increasingly intensified in this region.

3.2. Methods

3.2.1. Emergy Analysis Theory

Ecosystem services valuation methods include the economic valuation system and ecological valuation system. The economic valuation method has difficulties when services are not marketed. Emergy analysis is an ecological valuation method based on thermodynamic principles, which translates different inputs and outputs of an ecosystem into the same solar emjoule (sej) unit using solar energy as the base energy [37]. The emergy theory estimates the ecocentric value rather than the human-centric value [38,39]. This is in direct contrast to the economic view [39].

Although a controversial methodology, the emergy analysis offers a number of advantages, as it provides: (1) a way to bridge economic and ecological systems; (2) an objective means by which to quantify and value non-market inputs into a system; (3) a common unit that allows for a comparison of all resources; and (4) a more holistic alternative to many existing methods of decision-making. But critics of the emergy analysis generally complain that the method: (1) lacks formal links with related concepts in other disciplines; (2) lacks adequate details on the underlying methods; (3) is computationally and data intensive and (4) is based on sweeping generalizations that remain unproven [39–42]. Nowadays, emergy analysis is used to assess the sustainability of regional development, agricultural practices, and preservation and restoration of the natural environment, although controversy remains as to its use for ecosystem services valuation [40].

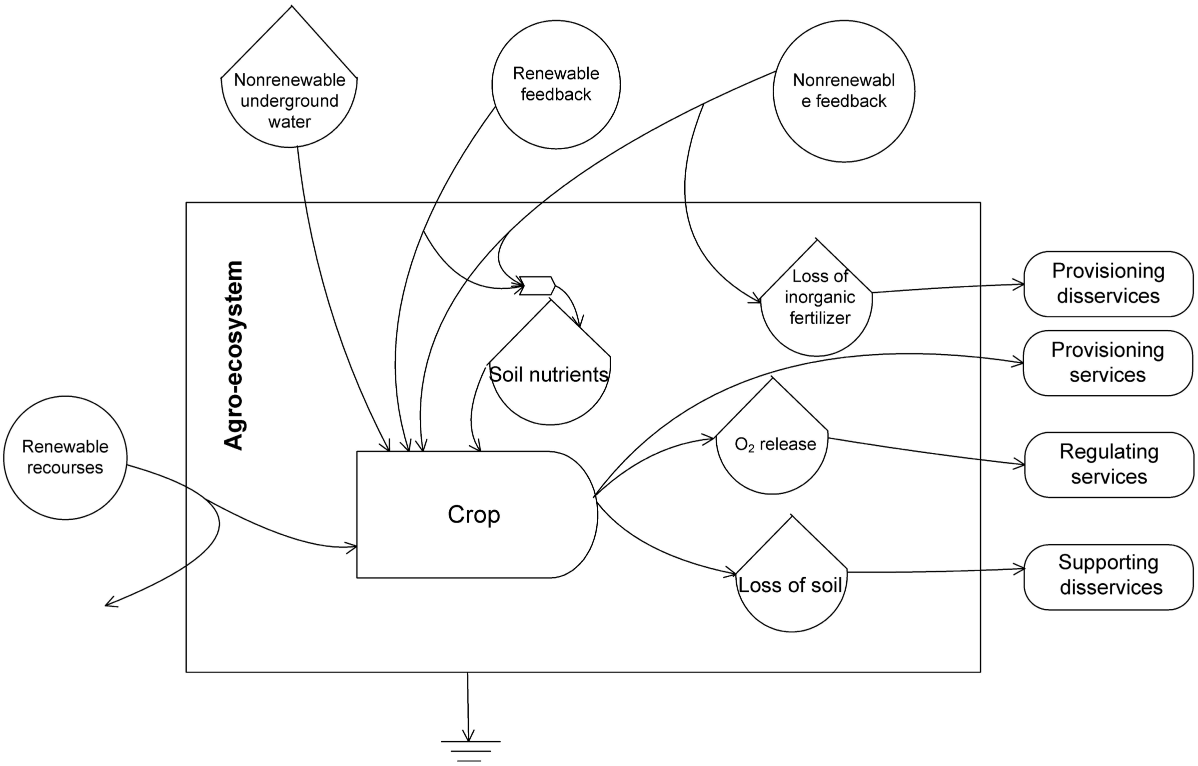
Based on the emergy theory, value does not only rely on human preferences and willingness to pay, but instead stems from the work of the biosphere to develop and stabilize an ecosystem structure, growth, organization, and diversity [43]. Jørgensen and Nielsen [44] stated that a complete diagnosis, focused on the ecosystem services, could be developed through the use of complementary indicators such as emergy and eco-exergy. Pulselli *et al.* [45] considered ecosystem services as a counterpart of emergy flows to ecosystem. Although the valuation methodology has no consensus, some studies [43,45–50] had tried to link the ecosystem services and emergy analysis, which is an evaluation from a donor-side approach [51,52].

3.2.2. Data Collection

The inputs and outputs structures in an agro-ecosystem are illustrated succinctly in Figure 2.

Data sources: Long-term (1984–2008) annual mean climatic data for solar radiation and rainfall were taken from the National Ecosystem Research Network of China and Luancheng County weather station. Socioeconomic data were obtained from statistical yearbooks of the local government. Soil data were taken from the National Ecosystem Research Network of China, the second national soil survey data, and relevant literature. Other parameters like products' economic coefficient, the price value of O_2 release, CO_2 fixation, *etc.* were obtained from the literature (see Table A1).

Figure 2. Emergy flows in the agro-ecosystem.



3.2.3. Data Analysis

All the data (indicators) were standardized using the emergy analysis method. This was done by transforming the different inputs and outputs into energy or mass data and then multiplying by the appropriate transformities (cited from the literature or calculated from our data) to obtain the emergy (see Table A1). Relationships between different services and the consumption resources were analyzed by bivariate correlation and step-wise linear regression using the SPSS and EViews software.

4. Results and Discussion

4.1. Summary of Different Indicators in the Agro-Ecosystem of Luancheng County

The calculated emergy values of basic structures (inputs and outputs) are shown in Table 1. The uncertainties, which referred to parameter uncertainties (u^2) in this paper, were measured by the Variance method [53,54]. As can be seen from Table 1, the largest inputs to the ecosystem were underground water, inorganic fertilizer, machines and tools, and fossil fuel. The use of machines and tools increased considerably over the years due to intensive mechanization of farm operations. Underground water showed a very large variability; with zero inputs in some years, rainfall was high enough to sustain crops. The largest inputs were those of the economic feedback resources (see Figure 1), except underground water, which counts as a nonrenewable resource. Both economic feedback resources and underground water are nonrenewable resources that have exerted an enormous pressure on the sustainability of the agro-ecosystem.

The inputs resources of Chinese agriculture generally were not the same as those in Luancheng County [55]. For example, water is south China was taken as a renewable resource, considering that rainfall and surface water are relatively abundant there. Also, the proportion of renewable resources was much lower than the nonrenewable feedback resources. In addition, the biggest input of nonrenewable resources in Chinese agriculture was inorganic fertilizer, rather than the machines and tools in Luancheng County. There are two reasons for this phenomenon: (1) the mechanization of agriculture in Luancheng County has been more complete than in other regions because about 66% of China's land area is mountainous, which is a great limitation to the use of large agricultural machines; and (2) the irrigation water in Luancheng County depends on underground water, which needs more machines to pump the water from underground.

Table 1. Classical statistics of the calculated emergy.

	Unit	Number	Minimum	Maximum	Mean	Standard Deviation	Uncertainty
Input resources							
Solar energy absorbed	10^{18} sej	25	1.13	1.74	1.47	0.14	0.02
Rain (geopotential)	10^{17} sej	25	3.23	11.21	5.49	1.66	2.76
Rain (chemical)	10^{18} sej	25	5.65	19.59	9.60	2.91	8.47
Underground water energy	10^{19} sej	25	0	9.44	3.91	2.94	8.64
Seeds	10^{18} sej	25	4.58	9.84	6.37	1.74	3.03
Human labor	10^{18} sej	25	3.39	9.90	6.68	2.50	6.25
Organic fertilizer	10^{17} sej	25	0.37	1.41	1.07	0.39	0.15
Inorganic fertilizer	10^{19} sej	25	3.54	7.85	5.68	1.12	1.25
Pesticides	10^{17} sej	25	0	6.85	3.70	2.35	5.52
Mulch	10^{16} sej	25	0	3.61	1.28	1.42	2.02
Machines and tools	10^{20} sej	25	0.40	1.68	1.09	0.53	0.28
Fossil fuel	10^{19} sej	25	2.77	8.05	4.68	1.72	2.96
Output ecosystem services and disservices							
Wheat	10^{20} sej	25	1.09	1.88	1.44	0.22	0.05
Corn	10^{20} sej	25	0.15	2.17	1.69	0.41	0.17
Oil seeds	10^{19} sej	25	0.16	1.05	0.44	3.75	14.1
Cotton	10^{19} sej	25	0	9.92	1.29	2.11	4.45
O_2 release	10^{20} sej	25	0.90	2.14	1.70	0.29	0.08
CO_2 fixation	10^{20} sej	24	−3.4	3.46	0.41	1.73	2.99
Nitrogen	10^{19} sej	12	1.77	3.63	2.92	0.49	0.24
Phosphorus	10^{19} sej	12	0.61	4.21	1.82	1.03	1.06
Potassium	10^{19} sej	11	0.89	1.44	1.24	0.14	0.02
Loss of inorganic fertilizer	10^{19} sej	25	0.96	2.10	1.52	0.30	0.09
Loss of soil	10^{18} sej	25	1.86	3.86	2.90	0.48	0.23

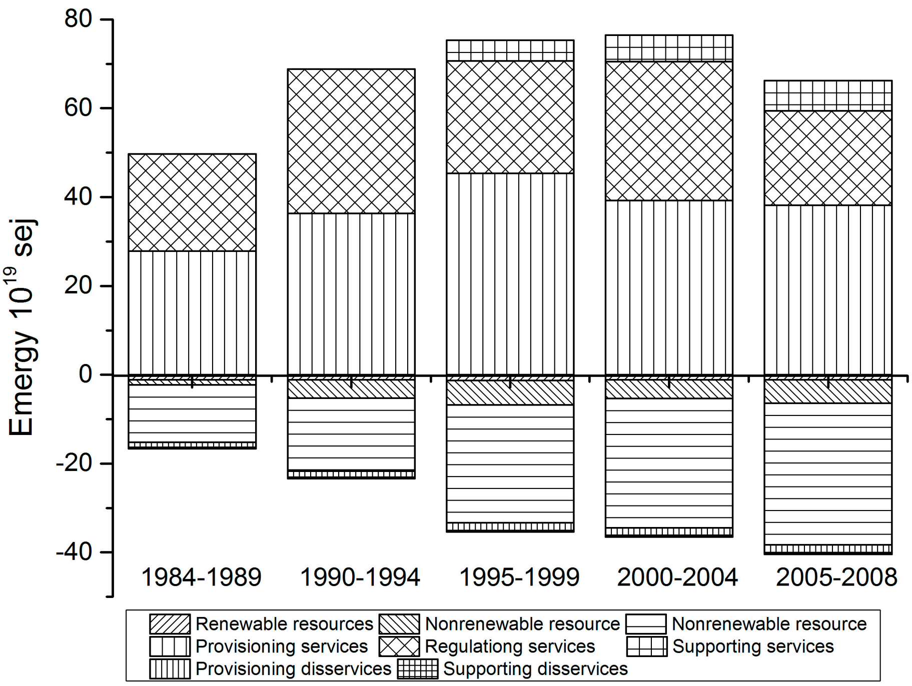
The largest output indicators were wheat, corn, O_2 release, and CO_2 fixation (see Table 1). Ecosystem provisioning services outputs ,which are the main benefits from the agro-ecosystem under study, are indicated mainly by yields of wheat and corn (the two major crops in the area; they also gave the largest outputs). The O_2 release and CO_2 fixation, which are regulating services, have always been ignored, although their values were as large as those of wheat and corn. For the ecosystem disservices outputs, losses of inorganic fertilizer and soil were much less than the main ecosystem services (Table 1). However, they tended to increase significantly over time and their effects may slowly become obvious in the future.

It has been confirmed that provisioning services were the largest output from an agro-ecosystem, whether based on the emergy analysis as in this work or on monetary valuation [28–30]. However, soil loss, which classifies as a supporting disservice, was quite different in this work from Chinese agriculture generally. Soil loss was classed as a nonrenewable natural resource and was "consumed" in so large an amount that it was only exceeded by inorganic fertilizer consumption [55]. It is true that lands that have undergone soil erosion account for almost one-third of total Chinese arable land, contrary to our observations in Luancheng County. However, the loss of soil was opposite to conserving soil (supporting services), so we defined it as supporting disservices rather than consumption in the agro-ecosystem.

4.2. Changes in Different Structures of Inputs and Outputs

The overall profile of the agro-ecosystem can be seen in Figure 3. The input resources were expressed in negative values since they were derived from other systems and consumed by the agro-ecosystem. The ecosystem services had positive values while disservices had negative values. Overall, the negative values increased consistently while the positive values increased firstly and then decreased. Specifically, the economic production system had the largest negative values (accounting for >70% of the total negative values) with a rising trend. The groundwater system followed with a fluctuating growth. The provisioning services showed mostly positive values, followed by the regulating services. Both of the main positive services increased at the initial period, only to decrease progressively thereafter. The raw data for supporting services were collected from 1998 to 2008 and the supporting services showed a stable trend during this period (Figure 3). The ecosystem services took a relatively small proportion.

Figure 3. Changes in different indicators of the agro-ecosystem of Luancheng County, China.



Previous research on agro-ecosystem services mainly focused on the benefits derived therefrom but the ecosystem disservices have become gradually recognized in recent years [27–30]. However, there is no consensus on these disservices. For example, some authors considered groundwater consumption as an ecosystem disservice [30], while some defined it as a regulating service [28,29]. Here, we consider it as a resource input from the groundwater system. If our analysis was performed based on the definitions of others, the results would be quite different. We defined ecosystem disservices as useless or harmful outcomes for humans. For example, loss of inorganic fertilizer is useless for humans but harmful to other ecosystems, such as eutrophication of water bodies or pollution of underground water. The potential disservice might be much larger than the emergy value of the loss of inorganic fertilizer. If our conceptual framework is supported by life cycle assessment, the value of ecosystem disservices might even be larger than that shown here.

4.3. Correlation between Different Services and Disservices

We explored the relationships between different indicators of services and disservices, considering there were some synergistic or trade-off relationship between different services. The results are shown in Table 2. The relationships between indicators of ecosystem services and disservices were mainly positive. Cotton production (provisioning services) and potassium and some of the phosphorus supplying services (supporting services) had negative correlations with other services. Cotton production negatively correlated with other services because the arable land was limited and wheat and corn competed for much of the cotton acreage. This also resulted in some possibility of a trade-off relationship between provisioning services, but not synergistic relationships. The reason for the negative relationship between potassium nutrients and other services was the imbalanced (or irrational) fertilization. Fertilizer application in the study area mainly focused on nitrogen fertilizer. The phosphate and, especially, potassium content of soil remained progressively low since they are applied as mere supplements to support the substantial increase in production. On the other hand, the nitrogen content showed a positive correlation, confirming that nitrogen fertilizer was applied excessively.

The relationships between other provisioning services and regulating services were synergistic, meaning that increasing the provisioning services brought about increases in regulating services without trade-off effects. However, the ecosystem disservices were also positively related with major services, suggesting that more and more burdens were imposed on the agro-ecosystem with its growing services.

Most previous studies have shown that growth in provisioning services resulted in a decline in regulating services [56]. For example, increasing the grain field was at the expense of increasing the level of soil erosion in mountain areas [57]. However, our research area had no significant reduction in regulating services because the agro-ecosystem had no serious soil erosion, given the plain terrain. The second reason for the negative correlation was the land use change—the conversion of forest or grassland to arable land, leading to a decline in regulating services and an increase in provisioning services. However, the agro-ecosystem of Luancheng County has been the same for a long time (having not been recently transformed from other ecosystems). In addition, the oxygen supply service was related to productive ability so that it kept increasing with the growing provisioning services. Thus, the relationship between provisioning services and regulating services is dependent on the area or location.

Table 2. Correlation (matrix) among different services and disservices of the agro-ecosystem in Luancheng County, China.

	Corn	**Oilseeds**	**Cotton**	**O_2 release**	**CO_2 fixation**	**Nitrogen**	**Phosphorus**	**Potassium**	**Loss of chemical fertilizer**	**Loss of soil**
Wheat	0.532	0.502	−0.451	0.924 **	0.21	0.374	−0.422	−0.568	0.194	−0.070
Corn		0.451	−0.850 **	0.797 **	−0.073	0.824 **	0.04	−0.261	0.664 **	0.713 **
Oilseeds			−0.615 *	0.631 *	0.093	0.255	−0.303	−0.126	0.249	0.124
Cotton				−0.706 *	−0.068	−0.765 **	−0.105	0.159	−0.779 **	−0.653 *
O_2 release					0.155	0.596 *	−0.308	−0.485	0.416	0.345
CO_2 fixation						0.128	0.011	−0.049	0.067	0.462
Nitrogen							0.171	−0.132	0.509	0.679 *
Phosphorus								0.454	0.117	0.369
Potassium									−0.144	0.205
Loss of chemical fertilizer										0.676 *

Note: ** $p < 0.01$, * $p < 0.05$.

4.4. Regression Analysis of Resource Inputs and Major Services Outputs

Provisioning services are the only focus of an agro-ecosystem regardless of other long-term services and disservices. Farmers apply very large inputs (consumptions) in order to get more yields from the fields. We took wheat and corn yields as examples and performed a regression analysis to explore the contributions of different resources to the yields, considering that wheat and corn account for 85% of all provisioning services in Luancheng County. The resulting regression equation for wheat was (see Table 3):

$$Y_w = 7.304 \times 10^{19} + 1.009G + 6.488 \times R + 0.731 \times F \quad (1)$$

where Y_W was wheat yield, G was groundwater resources, R was rainfall resources, and F was fossil fuel. We used a stepwise regression algorithm to obtain this regression equation. The Ramsey's regression specification error test (Ramsey RESET) was used to determine the appropriateness of the linear relationship using EViews software. The probability of F-statistic was 0.1601, being larger than 0.1. Since the functional form was valid at the confidence level of 0.1, we established that the most effective indicators were underground water, rainfall, and fossil fuel. The fossil fuel was used in the regression equation because it was needed for pumping groundwater for irrigation.

Table 3. Results of multiple stepwise regression analysis.

Services	Variables	Coefficients	Standard Error	t-value	Sig. (*p*-value)
Wheat	Constant	7.30×10^{19}	1.49×10^{19}	4.89	0
	Groundwater	1.009	0.139	7.273	0
	Rainfall	6.488	1.218	5.328	0
	Fossil fuel	−0.731	0.18	−4.064	0.001
	Adjusted R^2		0.675		
	Standard Error of the Estimate		1.27×10^{19}		
Corn	Constant	5.38×10^{19}	3.30×10^{19}	1.629	0.118
	Fertilizer	1.693	0.635	2.667	0.014
	Groundwater	0.485	0.243	2	0.058
	Adjusted R^2		0.449		
	Standard Error of the Estimate		3.05×10^{19}		
O_2 release	Constant	4.98×10^{19}	1.55×10^{19}	3.207	0.004
	Groundwater	1.155	0.121	9.524	
	Rainfall	7.372	1.161	6.348	
	Adjusted R^2		0.787		
	Standard Error of the Estimate		1.33×10^{19}		

We then performed path analysis to decompose correlations into different components, considering that explanatory variables could interact with each other. The results of path analysis are shown in Table 4. Both the Pearson correction coefficient, which is equal to the sum of the direct and indirect path coefficients, and the direct path coefficient of underground water were the largest. Although fossil fuel had the biggest indirect path coefficient, its Pearson correction coefficient was negative. This is because the input of fossil fuel was greater for years with less rainfall, in which the yields of wheat were relatively low. The independents were rain water, groundwater, and fuel for extracting water (fossil). This suggests that wheat production depends heavily on water, especially underground water.

Table 4. Summary of correlation coefficients for wheat.

Explanatory variables	Pearson correction coefficient	Direct path coefficient	Indirect path coefficients			
			Underground water	Rainfall	Fossil fuel	Total
Underground water	0.521	1.328		−0.582476	−0.224238	−0.806714
Rainfall	0.016	0.892	−0.867184		−0.010116	−0.8773
Fossil fuel	−0.017	−0.562	0.529872	0.016056		0.545928

The regression equation for corn was (see Table 3):

$$Y_c = 5.379 \times 10^{19} + 1.693 \times C + 0.485 \times G \quad (2)$$

where Y_c was corn yield, C was the fertilizer resource, and G was the groundwater resource. A Ramsey RESET test showed that the probability of F-statistic was 0.0468, being larger than 0.01, hence the functional form was correct at the confidence level of 0.01. The water supply was not included in the regression because the corn grew during the rainy season (June to September) and the rainfall is usually sufficient for growth. The results of path analysis are shown in Table 5. The supply of fertilizer had a larger direct path coefficient and the underground water had larger indirect path coefficients with corn yield. The Pearson correction coefficient of fertilizer was little larger than for the underground water, showing that both fertilizer and underground water were important inputs for corn.

Table 5. Summary of correlation coefficients for corn.

Explanatory variables	Pearson correction coefficient	Direct path coefficient	Indirect path coefficients		
			Fertilizer	Underground water	Total
Fertilizer	0.635	0.464		0.170868	0.170868
Underground water	0.576	0.348	0.227824		0.227824

It could be seen that different provisioning services were sensitive to different resources from the regressions of the major crop yield. Therefore, we should rationally allocate the different resources according to crop requirements.

In addition to provisioning services, the regulating services were also important ecosystem services in which oxygen release accounted for >80%. So we performed a regression analysis of oxygen release service and the resulting equation was (see Table 3):

$$Y_o = 4.980 \times 10^{19} + 1.155 \times G + 7.372 \times R \quad (3)$$

where Y_o was oxygen release, G was the groundwater resource, and R was the rainfall resource. A Ramsey RESET test showed that the probability of F-statistic was 0.1919, which was larger than 0.1. Therefore, the functional form was correct at the confidence level of 0.1.The contributory factors were only groundwater and rainfall, both being water resources. The results of path analysis (Table 6) showed that both the direct and indirect path coefficients of underground water were larger than those of rainfall, hence the Pearson correction coefficient of underground water was also larger. Thus, it could be noted that the regulating service, just like the provisioning services of wheat, was water-dependent and that water resources, especially underground water, directly determine how much service could be given.

Table 6. Summary of correlation coefficients for oxygen release.

Explanatory variables	Pearson correction coefficient	Direct path coefficient	Indirect path coefficients		
			Underground water	Rainfall	Total
Underground water	0.669	1.184		−0.515217	−0.515217
Rainfall	0.017	0.789	−0.773152		−0.773152

The influential factors of ecosystem services mainly center on land use change [58], climate change [59], and other natural factors [60], but the major driving factor differed according to region. The lack of water resources was the biggest challenge in North China. Our results also showed that the water resources directly determine the agro-ecosystem services and that groundwater supported this ecosystem. Thus, using the groundwater scientifically to optimize ecosystem services remains the key challenge in Luancheng County.

5. Conclusions

The high-yielding agro-ecosystem of Luancheng County in North China maintained provisioning services and regulating services but with increasing volatility with continued growth in farm (consumption) inputs and disservices outputs. Most of the relationships between different services and disservices of the agro-ecosystem were positive. However, cotton fields under provisioning services and soil potassium under supporting services had negative correlations with the others. The rainfall and groundwater resources were the most contributory input resources in the agro-ecosystem of Luancheng County and all other major ecosystem services depended on them directly.

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Author Contributions

Jintong Liu and Fengjiao Ma designed this research; Fengjiao Ma performed the calculations and analyzed the data; and A. Egrinya Eneji and Fengjiao Ma wrote the paper. All authors have read and approved the final manuscript.

Appendix

Table A1. Transformities, sources and formulation of raw data used for emergy analysis.

	Unit	Transformity (sej/unit)	Formulation of raw data	Sources of raw data
Solar radiation	J	1 [a]	Solar radiation = arable area × solar radiation intensity	e
Rain (geopotential)	J	8888 [a]	Rain geopotential = arable area × elevation × average rainfall × density × gravitational acceleration	e
Rain (chemical)	J	15,444 [a]	Rain chemical energy = arable area × average rainfall × Gibbs energy × density	e
Underground water	J	This study [(1)]		e
Seeds	J	7.86×10^4 [b]	Seed = amount of seed per unit area × arable area	f
Human labor	J	8.10×10^4 [c]	Human labor = the amount of human labor per unit area × arable area	f
Organic fertilizer	g	2.70×10^6 [a]	Organic fertilizer = amount of organic fertilizer per unit area × arable area	fg
Inorganic fertilizer	g	3.80×10^9 [d]	Raw data	h
Pesticide	g	1.60×10^9 [a]	Raw data	h
Mulch	g	3.80×10^8 [a]	Raw data	h
Machine and tools	J	7.50×10^7 [d]	Raw data	h
Fossil fuel	J	1.59×10^5 [a]	Raw data	h
Wheat	J	6.80×10^4 [a]	Wheat energy = wheat yield × wheat calorific value	gh
Corn	J	8.52×10^4 [d]	Corn energy = corn yield × corn calorific value	gh
Oilseeds	J	8.60×10^4 [a]	Oilseeds energy = oilseeds yield × oilseeds calorific value	gh
Cotton	J	8.60×10^5 [a]	Cotton energy = cotton yield × cotton calorific value	gh
O_2 release	$	4.94×10^{12} [c]	NPP = produce yield × (1-moisture content of each products) /each products economic coefficient Price of O_2 Release = NPP × (32/30) × the price of O_2 production	chi
CO_2 fixation	J	6.25×10^4 [a]	Energy of CO_2 fixation = accumulation of organic matter in soil × calorific value of organic matter	eglmno
Nitrogen	g	4.60×10^9 [c]	Nitrogen = arable area × topsoil thickness × density × percentage content of nitrogen	eglmno
Phosphorus	g	1.78×10^{10} [c]	Phosphorus = arable area × topsoil thickness × density × percentage content of Phosphorus	eglm

Table A1. *Cont.*

	Unit	Transformity (sej/unit)	Formulation of raw data	Sources of raw data
Potassium	g	1.74×10^{9} [c]	Potassium = arable area × topsoil thickness × density × percentage content of Potassium	eglmo
Loss of inorganic fertilizer	g	3.80×10^{9} [d]	Loss of inorganic fertilizer mass = mass of inorganic fertilizer × inorganic fertilizer loss rate	hq
Loss of soil		This study [(2)]		

Note: [(1)] Emergy of groundwater = energy of groundwater × transformity of groundwater. The amount of irrigation water was calculated using Yuan's approach [61]; this method relies on meteorological data and crop yield. Transformity of groundwater = energy of groundwater × transformity of rainfall × update time [62]; the relationship between groundwater update time (Y) and groundwater table (m) was Y = 0.13x + 6.73 in North China Plain, according to Wei [63]; [(2)] Emergy of topsoil loss = loss of topsoil organic matter × transformity of organic matter + loss of topsoil nitrogen × transformity of nitrogen+ loss of topsoil phosphorus × transformity of phosphorus + loss of topsoil potassium × transformity of potassium; [(3)] References for transformity: [a] [62]; [b] [64]; [c] [65]; [d] [66]; [(4)] References for raw data: e [67]; f [68]; g [69]; h Hebei Bureau of Statistics [70]; i Chinese Agricultural Yearbook [71]; j [72]; k State Forestry Administration [73]; l [74]; m [75]; n [76]; o [77]; p [78]; q [79]; r [80].

Conflicts of Interest

The authors declare no conflict of interest.

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