Postprint: Evaluation of Cropland Ecosystem Services and Irrigation Benefits in the North China Plain

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Abstract

While farmland ecosystems provide services such as agricultural products for humans, they also exert negative impacts on the ecological environment. Based on the Millennium Ecosystem Assessment (MA) framework, this study takes Luancheng District of Shijiazhuang City, Hebei Province—a typical high-yield farmland region in the North China Plain—as the research area, applies emergy theory to analyze farmland ecosystem inputs, and examines positive and negative service outputs of farmland ecosystems from three aspects: provisioning, regulating, and supporting; uses the apportionment coefficient method to calculate the net benefits of farmland irrigation, computes emergy indicators, and evaluates the sustainable development status of farmland ecosystems. The results show that: during the study period, the sum of non-renewable industrial auxiliary energy (6.81$×10^{11}$ sej · m^{-2}) and non-renewable environmental resources (groundwater for irrigation, 2.57$×10^{11}$ sej · m^{-2}) accounted for over 90% of the total annual emergy input (1.00$×10^{12}$ sej · m^{-2}) in the Luancheng farmland ecosystem, indicating that farmland ecosystems consume substantial amounts of non-renewable resources; the positive services provided by farmland (1.82$×10^{12}$ sej · m^{-2}) are primarily agricultural product provisioning (1.07$×10^{12}$ sej · m^{-2}), while negative services (5.87$×10^{11}$ sej · m^{-2}) are dominated by greenhouse gas emissions (5.31$×10^{11}$ sej · m^{-2}); considering the negative environmental impacts of farmland ecosystems, the calculated irrigation benefit apportionment coefficient for Luancheng farmland is 0.32, with a net irrigation benefit of 3.94$×10^{11}$ sej · m^{-2}, indicating relatively low irrigation benefits; the emergy sustainability indicator for Luancheng District ranges from 0.10 to 0.18, classifying it as a typical consumptive farmland ecosystem, and there is an urgent need to explore a truly high-quality farmland development path characterized by low energy consumption and high output to achieve healthy and sustainable development of farmland ecosystems.

Full Text

Evaluation of Agro-Ecosystem Services and Analysis of Irrigation Benefit in the North China Plain

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Abstract

Agro-ecosystems provide essential services such as agricultural products but also generate negative environmental impacts. Based on the Millennium Ecosystem Assessment (MA) framework, this study examines the high-yield farmland region of Luancheng District, Shijiazhuang City, Hebei Province, in the North China Plain. Using emergy theory, we analyzed agro-ecosystem inputs and quantified both positive and negative service outputs across three categories: provisioning, regulating, and supporting services. The sharing coefficient method was applied to calculate net irrigation benefits, and emergy indices were computed to evaluate the sustainability of the agro-ecosystem. Results show that during the study period, the average annual emergy input to Luancheng’ s agro-ecosystem was 1.00\$×10ˆ{12}\$ sej · m^{-2}, with over 90% derived from non-renewable industrial auxiliary emergy (6.81\$×10ˆ{11}\$ sej · m^{-2}) and non-renewable environmental resources (groundwater for irrigation, 2.57\$×10ˆ{11}\$ sej · m^{-2}), indicating substantial consumption of non-renewable resources. Positive services (1.82\$×10ˆ{12}\$ sej · m^{-2}) were dominated by agricultural product provisioning (1.07\$×10ˆ{12}\$ sej · m^{-2}), while negative services (5.87\$×10ˆ{11}\$ sej · m^{-2}) were primarily associated with greenhouse gas emissions (5.31\$×10ˆ{11}\$ sej · m^{-2}). Accounting for environmental costs, the irrigation benefit sharing coefficient was 0.32, yielding a net irrigation benefit of 3.94\$×10ˆ{11}\$ sej · m^{-2}—relatively low irrigation efficiency. Emergy sustainability indices ranged from 0.10 to 0.18, characterizing Luancheng’ s agro-ecosystem as a typical consumption-oriented system. The findings underscore an urgent need to develop genuine high-quality farmland pathways featuring low energy consumption and high output to achieve healthy, sustainable agro-ecosystem development.

Keywords: Agro-ecosystem; Emergy analysis; Sharing coefficient; Irrigation benefit; Ecosystem service; North China Plain

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Introduction

Water is the source of life, yet China' s per capita water resources amount to only 2,100 m^3, merely 28% of the global average. Agricultural water consumption accounts for 63.5% of national water use, representing the primary pathway of water resource depletion. The North China Plain, a critical national grain production base, relies on the high water-demand cropping system of winter wheat (*Triticum aestivum*) and summer maize (*Zea mays*). Coupled with low and unevenly distributed precipitation, this has resulted in the highest water resource development and utilization rate in China, yet severe water scarcity persists, significantly constraining agricultural development. To maintain high yields, farmland irrigation in the North China Plain primarily depends on groundwater extraction, leading to continuous declines in groundwater levels and triggering environmental problems such as land subsidence and water quality deterioration.

The sharing coefficient method represents a common approach for calculating irrigation benefits. Drawing on ecological economics and emergy theory, the irrigation benefit sharing coefficient is defined as the ratio of total emergy input from irrigation to total emergy input during production. This method comprehensively accounts for both economic system inputs and natural environmental inputs, providing more accurate calculations of agricultural irrigation inputs and outputs. However, previous applications of this method have often overlooked the negative environmental effects of agricultural production, such as non-point source pollution from pesticide and fertilizer runoff, soil erosion, greenhouse gas emissions, plastic film contamination, and groundwater over-exploitation, potentially resulting in overestimated irrigation benefits.

Recent studies have begun addressing these limitations. Bai et al. constructed an evaluation index system for farmland ecosystem services in the Haihe River Basin based on the Millennium Ecosystem Assessment (MA) framework, applying market value, shadow engineering, and opportunity cost methods to quantitatively assess both positive services (e.g., water conservation, oxygen release through photosynthesis, dust retention, carbon sequestration, soil nutrient accumulation) and negative services (environmental costs) in 2005. Yuan et al. used environmental economics methods to estimate ecosystem services in Luancheng, finding that agricultural production accounted for 38.1% of total ecosystem service value, while groundwater scarcity represented the most prominent environmental issue, comprising 76% of total environmental costs. Ma and Liu employed emergy theory to analyze Luancheng' s agro-ecosystem inputs and outputs from 1984 to 2008, revealing it as a high-consumption ecosystem providing substantial negative services, though their calculation did not account for environmental losses from groundwater over-exploitation.

Building on these foundations, this study uses Luancheng District—a typical representative of high-yield grain production in the North China Plain—as its research area. Adopting the MA ecosystem service classification system, we categorize Luancheng' s agro-ecosystem services into provisioning, regulating, and supporting services (cultural services were excluded due to their minimal presence). Using emergy theory, we analyze the input structure and service outputs (including both positive and negative services) of Luancheng' s agro-ecosystem, calculate the irrigation benefit sharing coefficient and net irrigation benefit, and evaluate system performance through emergy indicators. The results provide valuable references for sustainable water resource utilization, irrigation system optimization, and crop planting structure adjustment in the North China Plain.

1.1 Study Area

Luancheng District, Shijiazhuang City, Hebei Province (114°28 35 E–114°47 35 E, 37°41 34 N–38°01 07 N) is located in the alluvial fan plain at the northern foot of the Taihang Mountains in the North China Plain [Figure 1: see original paper]. The region features a warm temperate semi-humid monsoon climate with predominantly cinnamon soil. Cultivated land covers approximately 262.84 km^2, exceeding 75% of the district' s total area. The average annual temperature is 12.2°C, with 191 frost-free days and 2,544 hours of sunshine. Annual precipitation averages 483.5 mm (1949–2000), with 80% concentrated in July–September, severely mismatched with crop water requirements (approximately 1,000 mm) and critical growth periods. Consequently, substantial groundwater extraction is required to maintain high agricultural yields, and limited precipitation recharge has caused continuous groundwater level declines.

1.2 Methods

1.2.1 Emergy Theory Scientists have long sought a common metric for analyzing both natural environments and human economies. Emergy theory, developed by renowned ecologist H.T. Odum through extensive interdisciplinary research, resolves this challenge. Emergy is defined as the total available energy required directly and indirectly to produce a resource, product, or service. Using "solar emergy" as the baseline, the solar energy contained in a unit of energy or material represents its emergy transformity, measured in solar emjoules (sej). Emergy is calculated as:

$$\text{Emergy (sej)} = \text{Emergy transformity } (\text{sej} \cdot \text{unit}^{-1}) \times \text{Energy (or material mass)} \tag{1}$$

By converting different energy and material flows into emergy using transformities, diverse ecological flows can be unified for comprehensive analysis, providing a novel quantitative approach for eco-economic systems.

1.2.2 Data Collection and Compilation Data on Luancheng' s agro-ecosystem inputs and outputs from 1984–2008 were compiled from the *Shijiazhuang Statistical Yearbook*, *Hebei Province Water Resources Bulletin*, *Hebei Province Environmental Status Bulletin*, published literature, and related references. Input data included renewable environmental resources, non-renewable environmental resources, renewable organic auxiliary emergy, and non-renewable industrial auxiliary emergy. Output data encompassed both positive and negative services across provisioning, regulating, and supporting categories, with groundwater over-extraction incorporated into negative services.

1.2.3 Analytical Framework The analysis involved: (1) collecting input and output data for Luancheng' s agro-ecosystem; (2) determining emergy transformities for each indicator based on literature; (3) calculating emergy flows; (4) applying the sharing coefficient method to determine irrigation benefits; and (5) computing emergy indices for comprehensive evaluation.

1) Emergy Diagram: The emergy diagram for Luancheng' s agro-ecosystem was constructed using Odum' s energy system symbols to illustrate system structure, relationships between natural and socioeconomic components, and major emergy flows [Figure 2: see original paper].

2) Emergy Analysis Table: All input and output indicators were converted to emergy using Equation (1). The table includes emergy transformities and calculated values for 1984–2008 .

3) Irrigation Benefit Calculations: The irrigation benefit sharing coefficient ( ) and net irrigation benefit (E) were calculated as:

$$\varepsilon = \frac{I_{aw}}{I_t} \tag{2}$$

where I_{aw} is total irrigation emergy input (sum of water and facilities), and I_t is total agro-ecosystem emergy input (including renewable environmental resources, non-renewable environmental resources—primarily irrigation groundwater—renewable organic auxiliary emergy, and non-renewable industrial auxiliary emergy). Y_{net} represents net ecosystem service emergy; Y_p represents positive service emergy (sum of provisioning, regulating, and supporting services); and Y_n represents negative service emergy (sum of provisioning, regulating, and supporting negative services). Plastic film residual effects were excluded due to their minor contribution to total emergy input.

Groundwater over-extraction loss was calculated as:

$$E_{GW} = E_L \times A \times \tau_{GW} \times \frac{GGDP}{Pr} \tag{5}$$

where E_{GW} is groundwater over-extraction loss emergy (sej), E_L is a composite parameter for economic loss calculation (Equation 6), A is area (km^2), τ_{GW} is emergy transformity (sej · 10,000 yuan^{-1}), $GGDP$ is GDP per unit area (10,000 yuan · km^{-2}), and Pr is population density (persons · km^{-2}).

4) Emergy Indicators: Various emergy indices were calculated to comprehensively evaluate system performance.

2.1 Emergy Inputs in Luancheng Agro-Ecosystem

Emergy input-output calculations are presented in Table 2 . According to emergy theory, solar radiation, rain chemical energy, and rain geopotential energy all derive from solar radiation; to avoid double-counting, only the maximum value was included in renewable environmental resource inputs. Non-renewable industrial auxiliary emergy totaled 6.81$×10ˆ{11}$ sej · m^{-2} (67.81% of total input), indicating heavy dependence on fertilizers, pesticides, plastic film, and machinery as critical supports for high yields. Non-renewable environmental resources (primarily irrigation groundwater, 2.57$×10ˆ{11}$ sej · m^{-2}) accounted for 25.62% of total input. Together, these non-renewable inputs comprised 93.43% of total emergy, demonstrating that high yields come at the cost of substantial non-renewable resource consumption. Improving agricultural technology, promoting water-saving irrigation, and enhancing utilization of renewable resources like precipitation are essential for sustainable development.

2.2 Agro-Ecosystem Service Outputs

Based on the MA framework, positive and negative services were analyzed. Overall, positive services exceeded negative services [Figure 3: see original paper], with positive service emergy comprising 75.60% of total output (Table 2). Provisioning positive services dominated at 58.72% of total positive services, with maize contributing 45.79% of provisioning services. Regulating and supporting positive services accounted for 33.98% and 7.30%, respectively, highlighting the significant ecological functions of oxygen release and carbon sequestration alongside food production.

Negative service emergy represented 24.40% of total output, with regulating negative services exceeding 90% of total negative services, primarily from greenhouse gas emissions. Studies show that winter wheat fields in the North China Plain' s Taihang Mountain foothills are sources of CO_2 and N_2O, with nitrogen fertilization and irrigation promoting their generation. Groundwater over-extraction accounted for less than 1% of regulating negative services, likely due to methodological limitations and subjective parameter selection. However, groundwater over-extraction causes well failures, necessitates new infrastructure investment, and leads to deep soil contamination, land degradation, and biodiversity loss, making it a critical issue requiring urgent attention.

2.3 Irrigation Benefits

Using Luancheng' s emergy input-output data, the irrigation benefit sharing coefficient and net benefit were calculated . The sharing coefficient was 0.32, consistent with values reported by Cheng et al. and Luo et al. Net irrigation benefit was 3.94$×10^{11}$ sej · m^{-2}. Experimental studies in Xingtai reported sharing coefficients ranging 0.34–0.60 depending on crops, irrigation types, and water amounts. Wu and Xu summarized that typical sharing coefficients range 0.20–0.60 (average 0.40), with lower values in high-productivity regions. Luancheng' s coefficient of 0.32 falls within this range and reflects its high agricultural productivity level, validating our results.

The 25-year average net irrigation benefit was 3.94$×10^{11}$ sej · m^{-2}. Subtracting total irrigation input emergy plus groundwater over-extraction loss (3.24$×10^{11}$ sej · m^{-2}) from this value yields 7.0$×10^{10}$ sej · m^{-2}, representing the net benefit increment from irrigation or "emergy proliferation." However, this proliferation actually derives from other energy inputs like solar radiation.

2.4 Emergy Indicator Analysis

Based on agro-ecosystem characteristics and previous research, we constructed input-output indices, emergy source indices, ecological service indices, and comprehensive indices to quantitatively analyze system function and sustainability (Table 4).

2.4.1 Emergy Self-Sufficiency Ratio and Emergy Investment Ratio

The emergy self-sufficiency ratio measures the proportion of free environmental resources in total energy input, reflecting system self-sufficiency. The emergy investment ratio is the ratio of total auxiliary emergy input to environmental resource input, indicating economic development level and environmental dependence. Lower self-sufficiency and higher investment ratios signify greater economic input dependence. Luancheng' s average emergy self-sufficiency ratio was 0.28 and investment ratio 2.52 (1984–2008), similar to values reported for Huan County, Shandong (0.28 and 2.55 in 1996), indicating low contribution from environmental resources and high economic input dependence.

2.4.2 Environmental Loading Ratio The environmental loading ratio (ELR) is the ratio of non-renewable emergy input to renewable emergy, reflecting environmental pressure. Luancheng' s average ELR was 14.23, far exceeding

2003 Shandong (6.54), 2005 Jiangsu (2.83), and 2005 Hebei (5.72) averages, indicating substantial environmental pressure. This likely stems from high irrigation inputs and non-renewable industrial auxiliary emergy. With deep groundwater as the primary irrigation source and increasing industrial auxiliary emergy, Luancheng' s agro-ecosystem shows high fossil fuel consumption and dependency, necessitating environmental protection alongside yield increases.

2.4.3 Emergy Yield Ratio We analyzed both emergy economic yield ratio and emergy natural yield ratio, representing system advantages and sustainability in obtaining economic versus natural resource inputs. Odum suggests a reasonable economic yield ratio of 1-6; values below 1 indicate no emergy increase. Luancheng' s three economic yield ratios ranged 1.48–2.53, higher than Huan County (0.98 in 2006) and Hebei (0.73 in 2005) but still in the lower range, suggesting need for improvement. Natural yield ratios (3.74–6.38) were significantly higher than economic yield ratios due to lower natural system input (28.39%) versus economic input (71.61%). Non-renewable environmental resource input was 9.25 times renewable input, indicating excessive dependence on irrigation groundwater and creating a structural contradiction between water scarcity and agricultural demands.

2.4.4 Comprehensive Emergy Sustainability Index The comprehensive emergy sustainability index is defined as the ratio of emergy economic yield ratio to environmental loading ratio, evaluating eco-economic system sustainability. Luancheng' s three sustainability indices ranged 0.10–0.18, far below Huan County (0.72 in 1996), Shandong (1.52 in 2003), Jiangsu (0.68 in 2005), Yancheng (0.97 in 1995–2006), and Zhangye (1.216 in 1999). Ulgiati and Brown suggest values below 1 indicate consumption-oriented systems. Our results show Luancheng' s emergy output is obtained through high resource consumption, creating substantial environmental pressure and poor sustainability. Adjusting planting structures, developing green/ecological agriculture, and conserving groundwater are essential for sustainable development.

Discussion

Since the 1970s, Chinese scholars have addressed environmental issues from agricultural production. Overuse of inorganic fertilizers, pesticides, plastic film, and groundwater has caused soil compaction, non-point source pollution, and groundwater over-exploitation. However, methodological limitations have constrained most studies to single issues rather than holistic system analysis. Emergy analysis solves this by converting diverse input-output elements into unified solar emergy, overcoming measurement challenges from different units.

Notably, definitions vary among scholars regarding whether topsoil loss belongs to input or output modules, affecting comparability. Additionally, environmental issues are complex and interrelated—groundwater over-extraction directly causes water table declines and infrastructure failure while indirectly facilitating deep soil contamination and biodiversity loss. Comprehensive measurement requires scientifically sound definitions and innovative techniques.

The irrigation benefit sharing coefficient assumes a linear relationship between input and output ratios, which has limitations. The Cobb-Douglas production function ($Y = AL^{\alpha}K^{\beta}$) exemplifies non-linear relationships, indicating this linear assumption is oversimplified.

Agricultural production aims for high yield, quality, efficiency, and low consumption. Our results show Luancheng’ s agro-ecosystem is a severe consumption-oriented system dependent on non-renewable resources (fertilizers, pesticides, irrigation groundwater). Effective measures include: (1) Groundwater conservation through “source expansion” (building water conservancy facilities, rainwater harvesting) and “consumption reduction” (drip/sprinkler irrigation, drought-resistant crop varieties); (2) Promoting green fertilizers and deep fertilizer application to improve utilization; (3) Developing low-toxicity pesticides and pest-resistant varieties with forecast-based prevention. Government support for agricultural research, policy tools (e.g., subsidies), and legal frameworks are crucial for safeguarding modern, high-yield, low-consumption agriculture.

Conclusion

Emergy analysis of Luancheng’ s agro-ecosystem reveals that non-renewable industrial auxiliary emergy dominated inputs, followed by non-renewable environmental resources (irrigation groundwater). Positive service emergy exceeded negative service emergy, with provisioning services (grain supply) dominant among positive services and climate regulation (greenhouse gas emissions, groundwater over-extraction) primary among negative services. The irrigation benefit sharing coefficient (0.32) and net irrigation benefit (3.94$×10^{11}$ sej·m^{-2}) indicate relatively low irrigation efficiency. Sustainability indices far below 1 demonstrate high dependence on economic inputs and non-renewable groundwater, creating substantial environmental pressure and poor sustainability. Urgent development of genuine high-standard farmland with low energy consumption and high output is needed for healthy, sustainable agro-ecosystem development.

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