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Spatial Analysis on Resource Utilization, Environmental Consequences and Sustainability of Rice–Crayfish Rotation System in Jianghan Plain, China

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Abstract: The rice–crayfish rotation system (RCR), originating in the Jianghan Plain, is developing rapidly in various regions of China and has been characterized by unbalanced regional development, which has also led to widespread concerns and discussion on its environmental impacts and sustainability. This study selects representative RCR production areas in the Jianghan Plain, including Jianli, Qianjiang, Shishou, Shayang, Gong'an and Honghu, to analyze resource inputs, resource utilization efficiency, environmental impacts and sustainability by employing the emergy analysis method. Our analysis of Jianli, Honghu, Qianjiang, Gong'an, Shishou and Shayang reports total emergy inputs ranging from 6.46×10^{16} to 8.25×10^{16}, with renewable rates between 78.38% and 84.34%. Shishou leads in the unit emergy value (5.58×10^{-1}) and the emergy yield ratio (5.30). The sustainability evaluation finds that the environmental loading ratio is from 0.19 to 0.28 and the emergy index for sustainable development varies between 1.27 and 3.00. This analysis indicates that the southern regions have higher inputs and efficiency, with southeastern areas showing lower environmental impact and higher sustainability. We also underscore the impact of non-renewable resources on environmental outcomes and sustainability, suggesting tailored development strategies for the rice–crayfish rotation system's optimization and sustainable growth.

Keywords: rice–crayfish rotation systems; emergy analysis; spatial analysis; pollution control; sustainable development

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1. Introduction

In an era when global environmental change and sustainable development are becoming core issues in contemporary society, research on the sustainability of eco-agricultural systems is particularly important [1]. The rice–crayfish integrated system emerged as an innovative agricultural ecological model, originating and rapidly expanding in the Jianghan Plain region [2]. This system showcases distinctive advantages such as optimizing resource allocation, increasing farmers' incomes and enhancing ecological benefits, thereby winning the favor of local governments and farmers alike [3]. However, alongside its rapid development, it faces potential challenges related to ecological pressure and resource utilization [3]. Considering the vast area of the Jianghan Plain and the variability in ecological environmental conditions and farming practices across different geographical locations, there could be significant spatial disparities in the sustainability of the rice–crayfish rotation system [4]. These disparities also pose challenges to the formulation of region-specific agricultural policies. Hence, examining the sustainability of these regions is pivotal for ensuring food security and effective resource distribution. It also serves to direct agricultural practices and mitigate environmental risks, contributing to the comprehensive enhancement of the system's sustainability [5]. Furthermore, exploring these spatial differences and their underlying causes is crucial for promoting the sustainable development of the rice–crayfish rotation system both regionally and nationally in China, potentially providing invaluable insights and guidance for similar agricultural ecosystems globally.

The RCR system optimizes vertical space and biodiversity within small ecosystems, maximizing the use of light, water, heat and biological resources in rice paddies to boost both ecological and economic outcomes [6]. Vigorously supported by the Chinese government, the system had expanded across approximately 1.4 million hectares by 2021. Notably, Hubei Province, characterized by its ideal climatic conditions and abundant resources, ranks at the forefront in terms of both cultivation area and production output [7]. However, its rapid expansion has increased the reliance on natural resources, intensifying environmental impacts [8]. While the system offers substantial economic benefits [9], including reduced use of fertilizers and pesticides, lower greenhouse emissions, improved soil properties and enhanced microbial activity [10], it also has negative impacts such as potential water quality degradation from nutrient runoff, increased eutrophication, disruption of aquatic life and possible soil salinization and indirect carbon emissions [11–14]. Additional challenges stem from non-standard farming practices and overinvestment in agricultural resources focused on crayfish production [15], leading to unsustainable practices such as the overuse of fertilizers and labor in some regions [16,17]. Despite the fact that the current rice–crayfish rotation farming system faces challenges related to non-point source pollution, it still holds a competitive advantage for sustainable development [18]. Currently, there are more studies on the sustainability of rice–crayfish rotations, and spatial variation studies are gradually emerging. Most of the sustainability studies on the rice–crayfish system have focused on the environmental and economic performance of rice-based cultivation systems such as the rice–crayfish rotation system, rice–wheat rotation system, including greenhouse gas emissions from farmland [19], the warming potential of rice paddies [20], nutrient utilization efficiency [21], etc. However, research specifically targeting the internal dynamics of the rice–crayfish rotation system remains relatively scarce and is not well quantified. Some studies addressing environmental differences between the rice–crayfish rotation system and co-cultivation have not considered regional variability. Spatially, research on the regional differences in the benefits of integrated rice–crayfish cultivation is limited and tends to focus on micro-case studies across multiple experimental sites rather than extensive contiguous areas [22]. Macroscopically, studies often base their analysis on geography to deduce the spatiotemporal evolution of rice–crayfish fields [15,23], without quantitatively assessing the system's ecological benefits. Sustainability research on rice–crayfish systems is mostly concentrated on single regions or aspects, lacking a systematic analysis of the spatial differences in sustainability across different regions.

The emergy evaluation method (EME), developed in the 1980s by renowned ecologist H.T. Odum, serves as a holistic analysis tool for ecosystem sustainability [24]. This method uses solar energy to convert the material flows—inputs, outputs and storages—of agricultural systems into equivalent solar energy units, aiding in assessing system stability and sustainability. The EME is widely used in environmental impact assessments and sustainability evaluations, especially in integrated rice-cultivation systems [25,26]. Emergy analysis focuses on resource utilization, environmental impact and efficiency by calculating the system's total emergy input, including solar energy, water, fertilizers and pesticides, and assessing their effects on the ecosystem's health. It uses metrics like the renewability ratio (%R) and UEV to evaluate emergy transformation efficiency and the emergy yield ratio (EYR), environmental loading ratio (ELR) and emergy sustainability index (ESI) to gauge ecological–economic sustainability [27,28]. Compared to other analyses, the life cycle assessment (LCA) mainly focuses on assessing single environmental impacts of the system, specifically on water, soil and gas. Nutrient balance analysis, focusing on the input and output of the elements, regards all nutrients not used in crop production as surplus and emitted from the system, overlooking nutrients retained in the soil. The EME provides a more comprehensive sustainability assessment by considering both economic and ecological inputs and outputs, offering a method to evaluate the ecological–economic sustainability of integrated rice-cultivation systems. In summary, extensive research has been conducted both domestically and internationally on the environmental impacts of integrated rice-crayfish cultivation systems [29,30]. However, most studies have focused on evaluating the advantages of standard rice–crayfish cultivation models over traditional rice farming systems, with little consideration given to uncontrollable factors in the production process or the exploration of environmental impact differences at a macro-spatial scale [4,29,31]. Current research on environmental risk management of rice–crayfish systems primarily centers on direct environmental factors such as pollutant emissions, while studies on the alignment of production inputs with natural resources like land and water are still inadequate [22,30]. Therefore, it is crucial to delve deeper into the internal development and environmental impact differences within major rice–crayfish production regions, particularly when geographical changes occur. Moreover, identifying and optimizing key production processes or nodes to mitigate environmental impacts is also essential.

The objectives of this research include the following: (1) furthering the limited body of EME research on rice–crayfish rotation systems; (2) quantifying and comparing the environmental impact differences of rice–crayfish rotation systems across various counties; (3) identifying the primary factors contributing to resource consumption and environmental pollution from rice–crayfish rotation systems; (4) providing references for government policy-making on the sustainable development of rice–crayfish rotation systems.

Therefore, this study employs the emergy evaluation method (EME) to conduct a quantitative analysis and comparison of resource inputs, utilization rates, environmental loads, and sustainability of the rice–crayfish rotation system (RCR) across six counties in the Jianghan Plain. By identifying the causes of the regional differences, we aim to propose specific measures to optimize the spatial distribution of the RCR in this area.

2. Method and Area

2.1. Study Area and System Description

The Jianghan Plain (N 29°26′–31°37′, E 111°14′–114°36′) is located in the south–central part of Hubei Province, China, which is an alluvial plain formed by the Yangtze River and the Han River, including 11 counties of Hubei Province (Figure 1). As the main production area for the rice–crayfish industry in China, the plain has a subtropical monsoon climate with an average annual precipitation of 1100–1300 mm, relatively flat terrain, starry lakes, intertwined water networks and abundant water resources, which is favorable to the development of the rice–crayfish industry [32]. In 2022, this region's crayfish production accounted for about 47.43% of China's total crayfish production of the integrated rice–crayfish system [7].

In the plain, six counties in Hubei Province have vigorously developed specifically rice–crayfish industries, including Qianjiang, Jianli, Honghu, Gongan, Shishou and Shayang, which has contributed to the industry's large scale and popularity. Among them, the farming output in Jianli reached 162,700 tons in 2022, making it the county with the highest annual crayfish production in China. Honghu, Qianjiang, Shayang, Gongan and Shishou also rank among the top 15 in the country in terms of crayfish production, with productions of 133,200 tons, 121,900 tons, 66,500 tons, 63,000 tons and 47,900 tons, respectively [7]. Therefore, this research selects six counties of Qianjiang, Jianli, Honghu, Gongan, Shishou and Shayang in the Jianghan Plain as the study area, representatively.

RCR is a traditional integrated rice–crayfish farming mode, but also the main mode in Jianghan Plain. The arthropods mentioned in this model that grow in the field are crayfish, also known as crawfish, being freshwater crustaceans resembling small lobsters. Moreover, the main rice variety in this study area is Huanghuazhan. It is crucial to construct the necessary field infrastructure before RCR production. Usually, at the first farming year, it is necessary to dig a ditch around the paddy field with a width of 2 m~2.5 m and a depth from 1 m to 1.5 m (the ditch pit accounts for no more than 10% of the paddy field area in principle) for crayfish growth. Meanwhile, the surrounding ridges are strengthened and raised so that there is no seepage or leakage of water, and a 3–5-m wide access for machines and tools is left on the side of the main road entering the field. Rice is usually sown after plowing from June to July and harvested from September to October annually. After the rice harvest, the fields are left fallow. In early February of the following year, the field is inundated, and crayfish fries are put into the surrounding ditches at a density ranging from 90 K to 120 K tails/ha. These crayfish then grow in the fields and are continuously harvested from March to June, until the next rice planting. Therefore, it is known as the two productions of rice and crayfish in the whole farming year. The RCR system is characterized by no conflict between crayfish breeding and rice cultivation with simple operation and low investment costs.

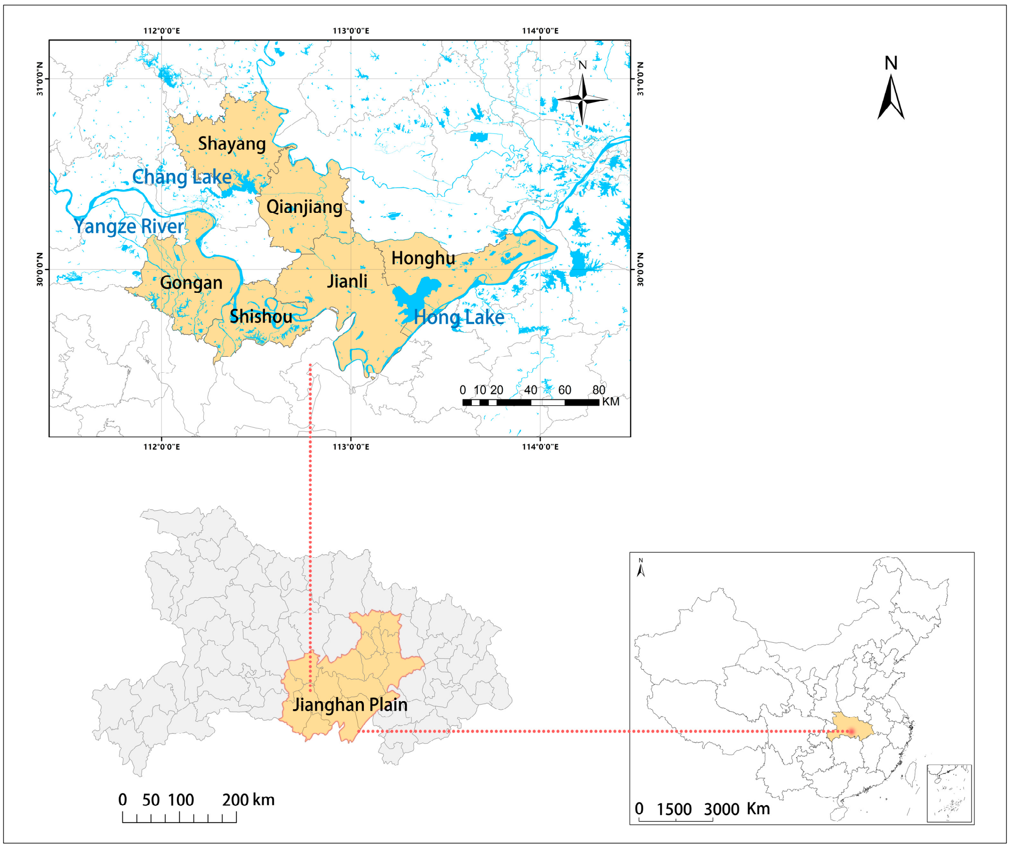

Figure 1. Location of the study area in China.

2.2. Farming Field Survey and Data Collection

Based on the comprehensive consideration of the rice–crayfish industry development and spatial differences, this research reviewed statistical yearbooks, government work reports, previous literature and consulted with local agricultural departments, which aimed to obtain the development status of the RCR in each county and identify the key towns of development. On this basis, this study selected key 3–4 towns in each of the above six counties as the study area, which represent the main production areas of the rice–crayfish rotation system in the Jianghan Plain. These include the towns of Bailu, Zhoulaozui and Futianji in Jiali County; Luishan and Wanquan in Honghu County; Jiyukou, Xiongkou and Haokou in Qianjiang County; Jizhuyuan, Shishikou, Mahaokou and Zhakou in Gongan County; Xiaoxiakou, Dongsheng and Tiaoguan in Shishou County; Mauri and Wulipu in Shayang County. This region is distributed according to the Yangtze River, the terrain is flat and the water system is developed, which is very favorable to the development of the rice–crayfish rotation system.

All original data for this study were gathered through field surveys conducted with farmers via questionnaires. This questionnaire was initially developed based on the previous literature and the specific cropping process of RCR, and then refined by the actual cultivation techniques observed during a preliminary survey in the study areas. This questionnaire consists of four sections: basic information about farmers and farmland, farming process, rice inputs and outputs, and crayfish feeding inputs and outputs, as detailed in Table 1. In 2021 and 2022, our research team randomly surveyed farming units within the study area, including small farmers, large-scale farmers, agricultural companies and agricultural industrial parks. The purpose was to ensure a broad and representative sample. In-depth field investigations were conducted to collect detailed data on agricultural practices such as the specific farming methods and key time points of RCR, inputs of seeds and crayfish fries, application of fertilizers and pesticides, feeds usage, mechanical and tool investments, labor costs, consumption of electricity, diesel, irrigation water and other related resources. The outputs of rice and crayfish, including their sales prices, were also meticulously recorded. All collected data were averaged over the two years of the study and converted to a per-hectare annual basis. Additionally, to confirm the accuracy and reliability of our data sources, we engaged with local government agricultural departments and frontline workers to gain insights into local RCR production processes and the focus areas for development. In total, 374 valid questionnaires were obtained, including 56 in Jianli, 53 in Honghu, 76 in Qianjiang, 65 in Gongan, 65 in Shishou and 59 in Shayang. The details of the categories and statistics of the original data are presented in Table 1.

Table 1. RCR inputs and output original data table (/ha/year).

Items		Jianli	Honghu	Qianjiang	Gongan	Shishou	Shayang	Unit
Input								
Rice seed		31.94	29.70	34.12	51.69	54.49	34.77	kg
Fry		443.88	403.59	417.67	458.66	456.37	324.44	kg
Fertilizer								
	N fertilizer	123.90	147.29	187.01	107.05	102.34	150.04	kg
	Compound fertilizer	413.78	395.92	506.68	1537.47	556.88	562.95	kg
Pesticide		4.31	2.92	3.72	3.82	4.15	4.13	kg
Medicine		127.39	22.90	131.68	112.41	102.46	163.18	kg
Diesel oil		0.08	0.09	0.10	0.10	0.09	0.07	t
Water		18,275.19	15,294.28	17,132.55	19,129.97	20,602.21	14,854.14	t
Electricity		1827.52	1529.43	1713.25	1913.00	2060.22	1485.41	kWh
Labor		31.45	94.66	43.90	49.51	50.46	52.38	person
Machine and tools		293.76	275.88	321.25	382.94	375.14	354.60	$
Feeds								
	Soybean	233.34	219.51	171.54	64.11	311.72	24.47	kg
	Compound forage	1417.10	951.39	1444.69	1537.47	1075.95	1316.65	kg
Plastic trap [a]		62.46	83.32	90.14	63.41	65.98	54.69	kg
Field facilities [b]		64.18	78.30	30.71	26.44	36.28	33.80	$
Anti-escape facilities [c]								
	Anti-escape net	1.29	1.43	0.97	1.34	1.14	0.92	kg
	Wooden sticks	27.00	33.00	22.00	25.00	34.50	24.30	kg
Aquatic plants		14.01	28.55	16.50	14.01	8.42	9.06	kg
Outputs								
Rice		9095.18	8253.82	9497.37	9245.28	8100.66	9144.69	kg
Crayfish		1999.72	1838.24	2325.77	2469.66	1398.35	1800.59	kg

Note. [a] The lifespan of the plastic trap is 3 years. [b] The lifespan of the field facilities is 10 years. [c] The lifespan of the anti-escape facility is 3.5 years.

2.3. Emergy Evaluation

In this research, the Emergy analysis method adopted a global emergency baseline of 1.20×10^{25} sej/year [27] as a reference point. It aimed to clarify the inflow and outflow of both renewable and non-renewable resources within the context of the rice–crayfish rotation system and examine emergy dynamics comprehensively. Then, it was possible to conduct a rigorous quantitative assessment of emergy production efficiency, environmental consequences and the overall sustainability of rice–crayfish rotation systems across the six counties in the main production regions of the Jianghan Plain.

2.3.1. Emergy Flow Diagram

Figure 2 shows the emergy flow of the rice–crayfish rotation system. Emergy resource inputs can be classified into three categories: (1) Free local renewable resources (L_R), such as sunlight, wind, rain and irrigation water; (2) Free local non-renewable resources (L_N), such as soil; (3) Economic purchased resources (P), such as rice seeds, fries, fertilizers, pesticides, diesel oil, electricity, anti-escape facility, feed, aquatic plants, labor machines and tools. In this case, according to the renewable factors (RNFs), the economic purchased resources (P) can be divided into renewable fraction of purchased resources (F_R) and non-renewable fraction of purchased resources (F_N). All items can be converted into solar energy values by multiplying unit emergy values (UEVs). The unit of solar energy value is solar emergy joules (sej). It is worth noting that straws left in the field and crayfish waste are considered internal energy flows within the system and, are thus not factored into emergy calculations [25].

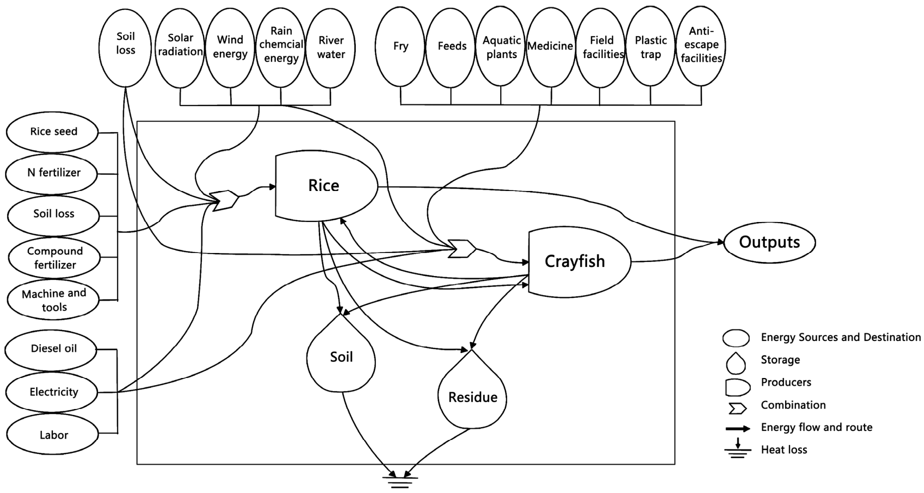

Figure 2. Energy flow diagram of RCR.

2.3.2. Emergy Analysis Table

The emergy analysis table in this study consists of six columns: number, item, raw data, solar emergy transformity, renewability factors (RNFs) and solar emergy value (Table 2). The "solar emergy value" is obtained by multiplying the "raw data" by the "solar emergy transformity".

Table 2. Emergy analysis of different rice-based rotation systems (ha/year).

Items	Unit	UEV (sej/Unit)	RNF	Emergy (sej)					
				Jianli	**Honghu**	**Qianjiang**	**Gongan**	**Shishou**	**Shayang**
Inputs									
Free local renewable resources (LR)									
Solar radiation	J	1	1	4.05×10^{13}	4.05×10^{13}	4.05×10^{13}	4.05×10^{13}	4.05×10^{13}	4.05×10^{13}
Wind energy	J	8.00×10^{2}	1	5.67×10^{12}	5.67×10^{12}	5.67×10^{12}	5.67×10^{12}	5.67×10^{12}	5.67×10^{12}
Rain chemical energy	J	7.00×10^{3}	1	3.46×10^{14}	3.46×10^{14}	3.46×10^{14}	3.46×10^{14}	3.46×10^{14}	3.46×10^{14}
River water (irrigation)	J	6.50×10^{4}	1	5.85×10^{16}	4.89×10^{16}	5.48×10^{16}	6.12×10^{16}	6.59×10^{16}	4.75×10^{16}
Free local non-renewable resources (LN)									
Soil loss	J	9.40×10^{4}	0	2.30×10^{14}	2.30×10^{14}	2.30×10^{14}	2.30×10^{14}	2.30×10^{14}	2.30×10^{14}
Economic purchased resources(P)									
Rice seed	g	2.55×10^{5}	1	1.30×10^{14}	1.21×10^{14}	1.39×10^{14}	2.11×10^{14}	2.22×10^{14}	1.42×10^{14}
Fry	g	1.27×10^{9}	0.2	5.64×10^{14}	5.13×10^{14}	5.30×10^{14}	5.82×10^{14}	5.80×10^{14}	4.12×10^{14}
N fertilizer	g	6.38×10^{9}	0	7.91×10^{14}	9.40×10^{14}	1.19×10^{15}	6.83×10^{14}	6.53×10^{14}	9.57×10^{14}
Compound fertilizer	g	3.56×10^{9}	0	1.47×10^{15}	1.41×10^{15}	1.80×10^{15}	5.47×10^{15}	1.98×10^{15}	2.00×10^{15}
Pesticide	g	1.89×10^{10}	0	8.14×10^{13}	5.52×10^{13}	7.03×10^{13}	7.23×10^{13}	7.85×10^{13}	7.81×10^{13}
Medicine	g	2.49×10^{10}	0	3.17×10^{15}	5.70×10^{14}	3.28×10^{15}	2.80×10^{15}	2.55×10^{15}	4.06×10^{15}
Diesel oil	J	4.09×10^{04}	0	1.52×10^{14}	1.76×10^{14}	1.87×10^{14}	1.84×10^{14}	1.65×10^{14}	1.34×10^{14}
Electricity	J	2.04×10^{05}	0.09	1.34×10^{15}	1.12×10^{15}	1.26×10^{15}	1.40×10^{15}	1.51×10^{15}	1.09×10^{15}
Labor	J	1.24×10^{06}	0.6	4.91×10^{14}	1.48×10^{15}	6.86×10^{14}	7.74×10^{14}	7.88×10^{14}	8.18×10^{14}
Machine and tools	$	5.81×10^{12}	0	1.71×10^{15}	1.60×10^{15}	1.87×10^{15}	2.22×10^{15}	2.18×10^{15}	2.06×10^{15}
Soybean	J	1.34×10^{05}	0.33	4.74×10^{14}	4.46×10^{14}	3.48×10^{14}	1.30×10^{14}	6.33×10^{14}	4.97×10^{13}
Compound forage	g	1.70×10^{09}	0.2	2.41×10^{15}	1.62×10^{15}	2.46×10^{15}	2.61×10^{15}	1.83×10^{15}	2.24×10^{15}
Plastic trap	g	1.87×10^{09}	0	1.17×10^{14}	1.56×10^{14}	1.69×10^{14}	1.19×10^{14}	1.23×10^{14}	1.02×10^{14}
Field facilities	$	5.81×10^{12}	0	3.73×10^{14}	4.55×10^{14}	1.78×10^{14}	1.54×10^{14}	2.11×10^{14}	1.96×10^{14}
Anti-escape nets	g	2.89×10^{08}	0	3.71×10^{11}	4.13×10^{11}	2.81×10^{11}	3.88×10^{11}	3.30×10^{11}	2.67×10^{11}
Wooden sticks	g	5.14×10^{08}	1	1.39×10^{13}	1.70×10^{13}	1.13×10^{13}	1.29×10^{13}	1.77×10^{13}	1.25×10^{13}
Aquatic plants	J	1.65×10^{04}	0.68	3.26×10^{15}	6.64×10^{15}	3.84×10^{15}	3.26×10^{15}	1.96×10^{15}	2.11×10^{15}
Outputs									
Rice	J	2.43×10^{05}	--	3.35×10^{16}	3.04×10^{16}	3.50×10^{16}	3.40×10^{16}	2.98×10^{16}	3.37×10^{16}
Crayfish	J	1.30×10^{07}	--	1.68×10^{17}	1.54×10^{17}	1.95×10^{17}	2.07×10^{17}	1.17×10^{17}	1.51×10^{17}

Table 2. *Cont.*

Items	Unit	UEV (sej/Unit)	RNF	Emergy (sej)					
				Jianli	**Honghu**	**Qianjiang**	**Gongan**	**Shishou**	**Shayang**
Emergy flows (sej)									
Free local renewable resources (L_R)				5.89×10^{16}	4.93×10^{16}	5.52×10^{16}	6.16×10^{16}	6.63×10^{16}	4.79×10^{16}
Free local non-renewable resources (L_N)				2.30×10^{14}	2.30×10^{14}	2.30×10^{14}	2.30×10^{14}	2.30×10^{14}	2.30×10^{14}
Economic purchased resources (F)				1.92×10^{16}	1.73×10^{16}	1.80×10^{16}	2.07×10^{16}	1.55×10^{16}	1.65×10^{16}
Renewable fraction of purchased resources (F_R)				6.22×10^{15}	6.22×10^{15}	4.00×10^{15}	3.71×10^{15}	2.87×10^{15}	2.72×10^{15}
Non-renewable fraction of purchased resources (F_N)				1.30×10^{16}	1.11×10^{16}	1.40×10^{16}	1.70×10^{16}	1.26×10^{16}	1.37×10^{16}
Renewable emergy flows ($L_R + F_R$)				6.51×10^{16}	5.55×10^{16}	5.92×10^{16}	6.53×10^{16}	6.92×10^{16}	5.06×10^{16}
Non-renewable emergy flows ($L_N + F_N$)				1.33×10^{16}	1.13×10^{16}	1.42×10^{16}	1.72×10^{16}	1.28×10^{16}	1.40×10^{16}
Total emergy inputs (U)				7.57×10^{16}	6.69×10^{16}	7.35×10^{16}	8.25×10^{16}	8.20×10^{16}	6.46×10^{16}
Total emergy outputs (Y)				2.01×10^{17}	1.85×10^{17}	2.30×10^{17}	2.41×10^{17}	1.47×10^{17}	1.85×10^{17}

This study uses RNF to measure the renewable capacity of socioeconomic resources. RNF and UEV refer to a wide range of factors. These include solar radiation, river water, soil loss and diesel oil [24] (as documented by Odum et al.). Additionally, wind energy and rain chemical energy are considered according to Brown and Ulgiati [27]. Lan et al. [28] discusses seeds, nitrogen (N), compound fertilizers, pesticides, wooden sticks, machinery and tools, field facilities and anti-escape nets. Meanwhile, Li et al. [33] focus on compound forage and fry. Lastly, Brown and Bardi [34] explore electricity, plastic traps and labor, while Buller et al. [35] delve into soybean and aquatic plants.

2.3.3. Establishment of Emergy Indices

Based on the analysis of the objectives of emergy evaluation in the rice–crayfish integrated farming system, this study selected emergy evaluation indices, as shown in Table 3. It is noteworthy that this study refers to a composite parameter as the environmental index of sustainable development (EISD) to provide a comprehensive evaluation of the sustainability of the rice–crayfish rotation system, departing from the conventional emergy sustainability index (ESI). This decision stemmed from the recognition that the essential functions of an ecological economic system encompass not only energy flows but also material cycles, financial transactions and information exchange. ESI, primarily assessing energy flow, falls short of meeting the comprehensive sustainability evaluation requirements of the system [36]. Notably, the environmental index of sustainable development (EISD) incorporates the analysis of energy flow, material flow and monetary flow, while considering multiple factors, including economic benefits, ecological advantages and regional environmental pressures. This approach offers a more encompassing reflection of the overall sustainability of the system [37] (Table 3).

Table 3. Emergy value evaluation indices.

Emergy Indices [a]	Expression [b]	Description
Unit emergy value (UEV)	UEV = U/Y	Evaluation of resource efficiency of output products.
Emergy self-support ratio (ESR)	ESR = (R + N)/U	Evaluation of the degree of utilization and dependence of the system on natural resources.
Renewable fraction (%R)	(R + FR)/U × 100%	Evaluation of the proportion of renewable resources utilized in the production process of the system.
Emergy yield ratio (EYR)	EYR = (R + N + F)/F	Describe the magnitude of the system's ability to profit from socio-economic resources.
Environmental load ratio (ELR)	ELR = (N + Fn)/(R + Fr)	Evaluation of the pressure of the system on the surrounding environment.
Emergy index for sustainable development (EISD)	[EYR × (Fr + Fn)]/Y × ELR	Capacity of the integrated evaluation system for sustainable development.

[a] UEV, ESR, %R, EYR, ELR, EISD derive from Odum [24], Brown and Ulgiati [26] and Lu et al. [37]. [b] U: Total emergy input, in an energy-balanced system, total emergy output = total emergy input; Y: System output (including products' mass, energy and money); L_R: The emergy of renewable natural resources; L_N: The emergy of non-renewable natural resources; F_R: The emergy of renewable economic imported resources; F_N: The emergy of non-renewable economic imported resources.

3. Result

3.1. Resource Input Analysis

3.1.1. Comparative Analysis of Resource Input Structure

Table 2 presents the emergy analysis results for the rice–crayfish rotation (RCR) system across six counties. Combined with Figure 3, Gong'an County records the highest total emergy input at 8.25×10^{16} sej, surpassing ShiShou (8.20×10^{16} sej), Jianli (7.57×10^{16} sej), Qianjiang (7.35×10^{16} sej), Honghu (6.69×10^{16} sej) and Shayang (6.46×10^{16} sej) by 0.6% to 28%. This implies that Gong'an's RCR system involves the greatest overall investment in natural and social resources, though the composition of these inputs differs across counties.

Figure 4 shows the emergy input proportions in the RCR systems by location, highlighting significant variations in resource allocation across six counties. L_R consistently dominate, while L_N resources, indicating topsoil loss, consistently account for less than 1%. Shishou uses the highest percentage of renewable resources (%R) at 84.34%, followed by Honghu, Jianli, Qianjiang and Gong'an, with Shayang at the lowest with 78.38%. This demonstrates Shishou's significant reliance on renewable resources, in contrast to Shayang's 21.3% in non-renewable resource inputs, the highest among the counties. The emergy sustainability ratio (ESR) further indicates Shishou's high dependency on natural resources at a rate of 0.81, while Honghu and Shayang show the least dependency at about 0.74, suggesting a greater reliance on economically purchased resources (Table 4). These disparities reflect the unique agricultural practices of each county and have profound implications for the environmental sustainability of the rice–crayfish systems in the Jianghan Plain.

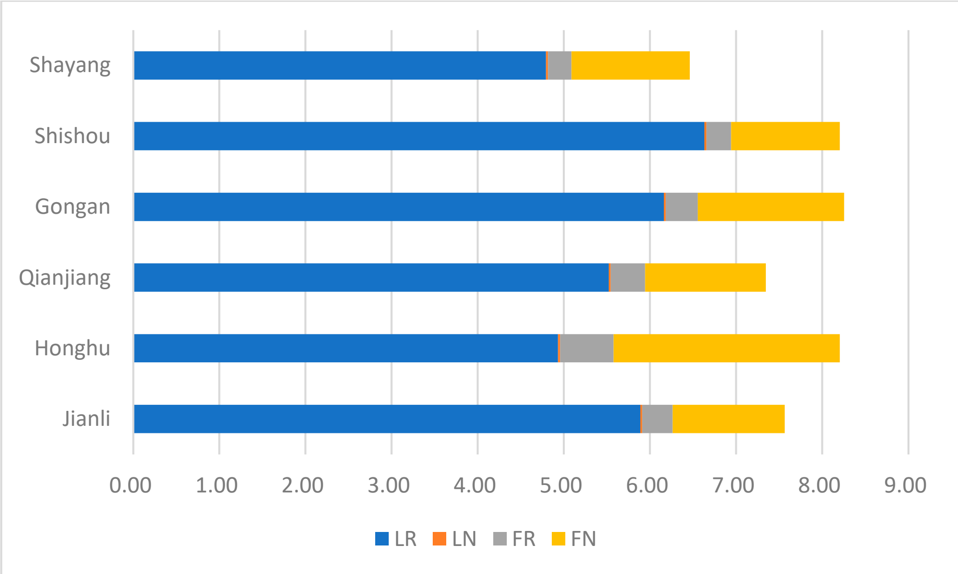

Figure 3. Structure and value of resource inputs in each region for RCR (Sejx10[16]).

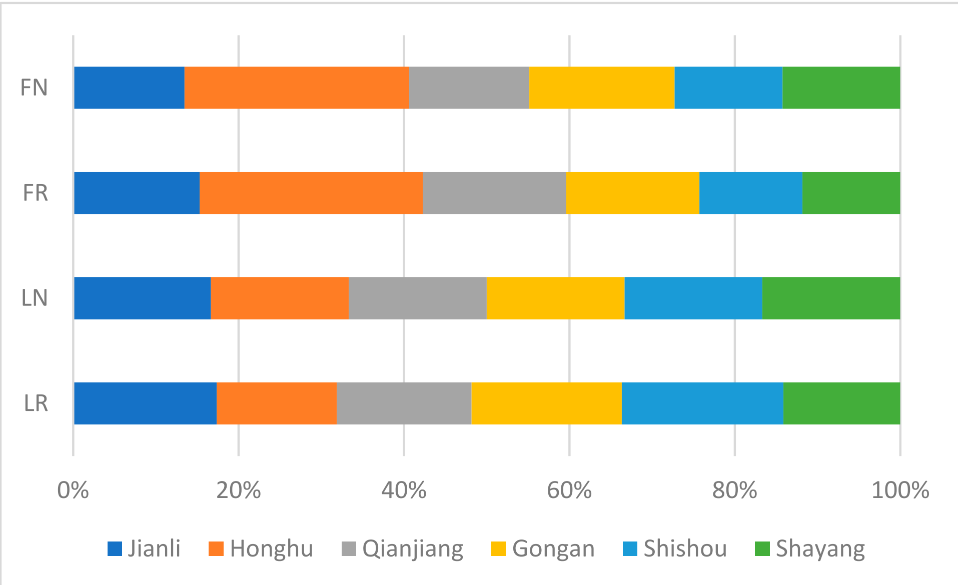

Figure 4. Proportion of resources invested in each region for RCR.

Table 4. Comparison of emergy indices for RCR in Jianghan Plain.

Indices	Jianli	Honghu	Qianjiang	Gongan	Shishou	Shayang
UEV	0.38	0.36	0.32	0.34	0.56	0.35
ESR	0.78	0.74	0.76	0.75	0.81	0.75
%R	82.48	83.05	80.61	79.14	84.34	78.38
EYR	4.57	3.86	4.08	3.99	5.30	3.92
ELR	0.21	0.20	0.24	0.26	0.19	0.28
EISD	1.77	1.78	1.33	1.30	3.00	1.27

From a spatial distribution perspective, the total emergy input (U) exhibits a trend of higher values in the south than in the north and higher in the west than in the east (Figure 5). Also, within the primary rice–crayfish production area of Jianghan Plain, the southwestern region along the Yangtze River exhibits higher values. The significant disparity in total emergy input among these regions is primarily influenced by local farming practices, as Gong'an exceeds Shayang by 28%. Figure 6 reveals that the spatial distribution of the renewable ratio (%R) of resource inputs across regions decreases from southeast to northwest. The values of the renewable ratio are in the ranges 78–80%, 80–82% and 82–85%, with their respective area proportions being 31.88%, 14.51% and 53.61%. This shows that the renewable rate of resource inputs for rice–crayfish rotation systems in the Jianghan Plain predominantly falls within the 82–85% range.

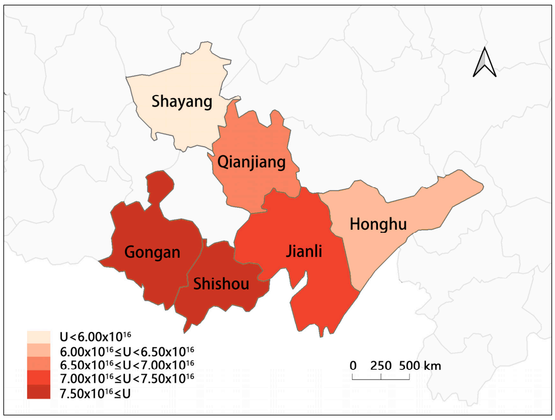

Figure 5. Spatial distribution of total inputs (U) for RCR (Sej).

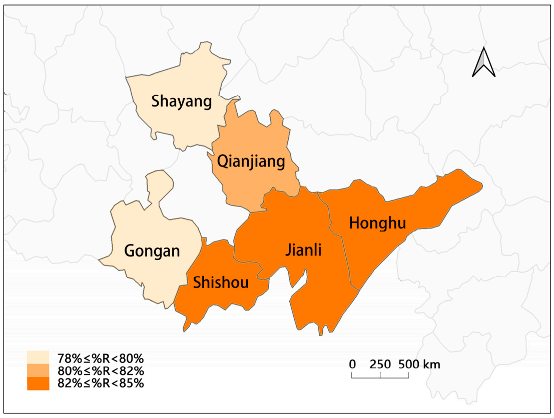

Figure 6. Spatial distribution of renewable fraction (%R) for RCR.

3.1.2. Comparative Analysis of Input Categories

Based on prior research, RCR systems involve a substantial input of economically purchased resources (F), significantly affecting the system's environmental footprint [29]. Our analysis across various regions (Figure 5) reveals that the main F inputs include compound fertilizers, medicines, machines and tools, feed and aquatic plants, though their proportions differ. Specifically, Gong'an leads with the highest inputs in compound fertilizers (5.47341×10^{15} sej), machinery (2.22488×10^{15} sej) and compound forage (2.61371×10^{15} sej), while Honghu reports the lowest in these categories (1.40949×10^{15} sej, 1.60285×10^{15} sej, and 1.61736×10^{15} sej, respectively). Shayang has the highest medicine input at 4.06319×10^{15} sej, contrasting with Honghu's lowest at 5.70279×10^{14} sej. Honghu also has the highest aquatic plant input at 6.6416×10^{15} sej, with Shishou contributing the least at 1.95852×10^{15} sej.

Referring to the proportion of F inputs, Jianli, Honghu and Qianjiang have aquatic plants as their highest input category, accounting for 20%, 35% and 21%, respectively. Gong'an and Shayang prefer compound fertilizers (26%) and medicines (25%), respectively, indicating their dependency on these inputs. This variation underscores the diverse specific needs across regions, influenced by local farming practices. Figures 7 and 8 show that compound fertilizers, medicines, machines, compound forage and aquatic plants are consistently top inputs across all regions, reflecting their critical role in the rice–crayfish production of the Jianghan Plain.

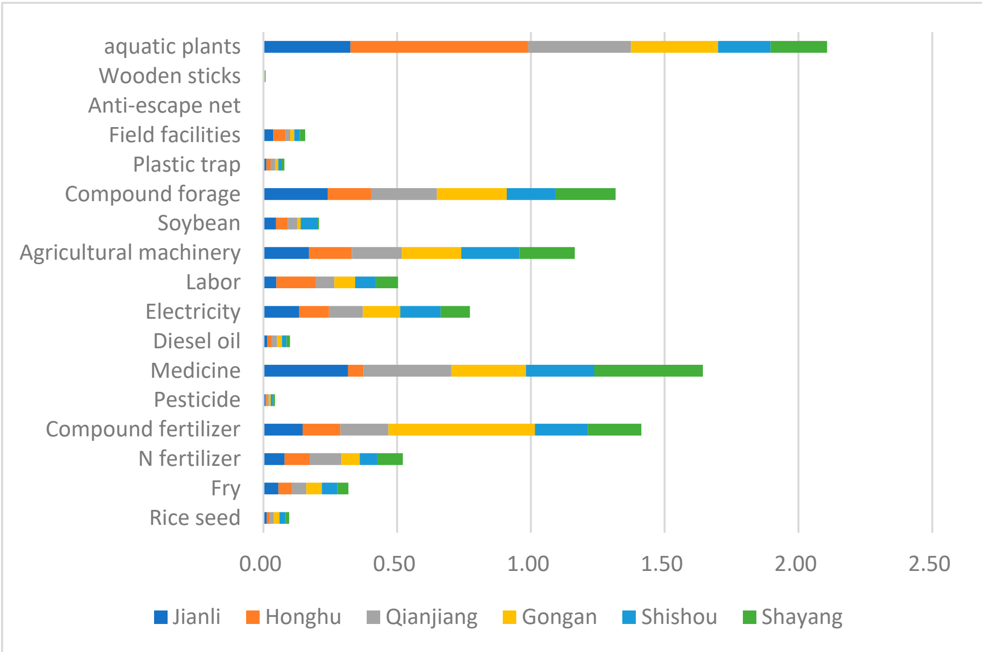

Figure 7. Detailed emergy value of economic purchased resource for RCR in each region (Sejx10[16]).

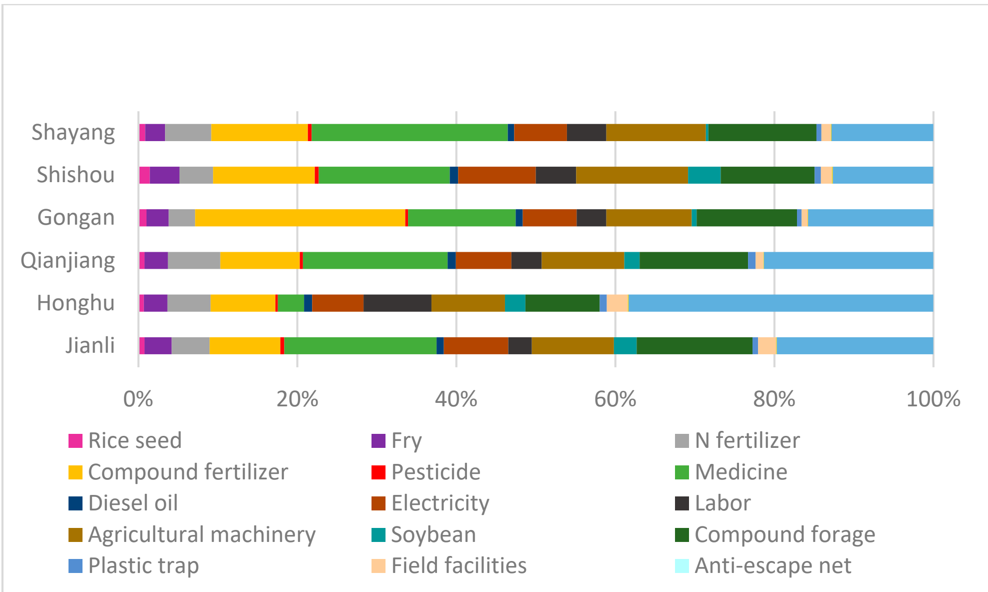

Figure 8. Detailed emergy proportion of economic purchased resources for RCR in each region.

Notably, the input amounts and their proportions of compound fertilizers and aquatic plants are highest in Gong'an and Honghu, respectively, indicating a priority in these inputs. Although Gong'an leads in the volume of machines and tools used, Shishou ranks highest in its proportion to other inputs. Similarly, Jianli shows the highest proportion for feed, attributed to the relatively lower proportions of other resources, causing discrepancies between volume and proportion rankings. This disparity in input volumes and their relative proportions across the Jianghan Plain's regions suggests varying environmental impacts. Although Gong'an has the largest input of machines and tools, Shishou boasts the highest proportion of such elements. For compound forage, Jianli has the highest proportion, while Gong'an leads in the total input volume. This mismatch between input volumes and proportions underscores the unique resource dependencies and potential environmental effects throughout the Jianghan Plain.

3.2. Nutrient Utilization Efficiency Analysis

3.2.1. Calculation of Nutrient Utilization

By calculating the amount of emergy required per unit of output in the rice–crayfish main production areas of the Jianghan Plain (Table 4), it is found that Shishou has the highest system unit emergy value (UEV) at 0.56, while Qianjiang has the lowest at 0.31. Therefore, Qianjiang boasts the highest emergy conversion efficiency, followed by Gong'an (0.34), Shayang (0.35), Honghu (0.36) and Jianli (0.38), with Shishou having the lowest efficiency. This indicates that Qianjiang leads the region in converting input resources into biomass and usable energy.

From the calculations of the emergy yield ratio (EYR) for RCR across the Jianghan Plain (Table 4), Shishou has the highest EYR at 5.30, followed by Jianli at 4.57, with Qianjiang (4.08), Gong'an (3.99) and Shayang (3.92). Honghu has the lowest at 3.86, approximately 70% of Shishou's EYR, indicating Shishou's superior capability in converting and utilizing F, while Honghu is the least efficient. Notably, Shishou has the highest UEV and EYR, demonstrating that it has the lowest overall input efficiency but a higher utilization efficiency of economic purchased resources.

3.2.2. Spatial Analysis of Nutrient Efficiency

Figures 6 and 9 illustrate that the distribution of the system unit emergy value (UEV) across regions follows a similar pattern to the %R, decreasing from southeast to northwest. The UEV values range between 0.319 and 0.558, concentrating between 0.32 and 0.38, located along the eastern coast of Hong Lake and both sides of the Yangtze River in the west, covering 75.16% of the research area. The difference between the highest and lowest values is significant, with Qianjiang's UEV approximately half that of Shishou, indicating that the southern area exhibits the highest total efficiency per unit, while the northern part has the lowest.

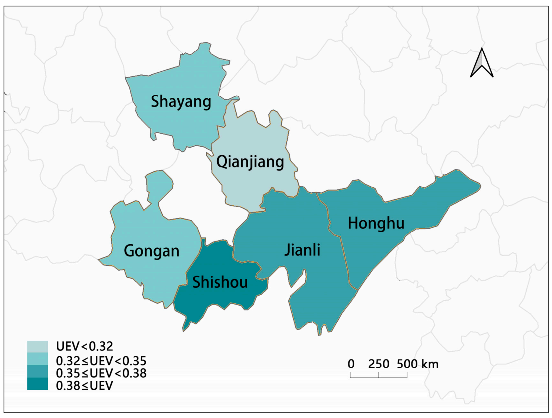

Figure 9. Spatial distribution of unit emergy value (UEV) for RCR.

More so, Figure 10 reveals that the EYR in the Jianghan Plain's primary rice–crayfish production areas primarily fall into three categories: higher efficiency (EYR > 5), medium efficiency (4 < EYR < 5) and lower efficiency (EYR < 4). The spatial distribution features higher rates in the middle area, and lower rates in both the eastern and western areas. The area of higher efficiency, primarily located in Shishou, only accounts for 10.33% of the total area. In contrast, the area of lower efficiency covers 50.11%, mainly found along the western banks of the Yangtze River and the east of Hong Lake, including Honghu, Gong'an and Shayang. This distribution is largely due to the region's reliance on non-renewable resources such as compound fertilizers, pesticides and medicines for crayfish farming (Figures 7 and 8). It can be seen that there is a large spatial difference in EYR values across the main RCR areas of Jianghan Plain.

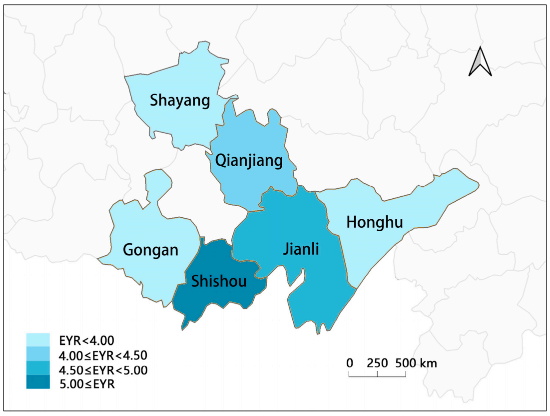

Figure 10. Spatial distribution of emergy yield ratio (EYR) for RCR.

3.3. Environmental Consequence and Sustainability Analysis

3.3.1. Result Calculation

As presented in Table 4, this study employs the EME with emergy indices to conduct an emergy evaluation for RCR primary production regions in Jianghan Plain. The value of ELR for six counties' RCR system is less than 3, indicating that the RCR systems in the Jianghan Plain have a relatively low environmental burden [26], though variations exist among the regions. Shishou has the lowest ELR at 0.19, with Shayang's ELR approximately 1.5 times higher than Shishou's. The ELR values of Gong'an, Qianjiang and Jianli are about 42% and 30% higher than Shishou's, respectively, while Honghu's ELR is slightly above Shishou's. This suggests that the environmental impact of RCR systems in Shishou, Honghu and Jianli is lower compared to other areas, with Shayang showing a notably higher impact.

Figures 3, 4 and 7 suggest that Shayang's highest ELR may result from its large proportion of non-renewable resources input of about 21%, especially in medicines, leading to substantial environmental pressure. According to Table 4, Shishou has the highest EISD at 3.0, with Honghu (1.78), Jianli (1.77), Qianjiang (1.33), Gong'an (1.30) and Shayang (1.27) experiencing declines in EISD of 40.7%, 41%, 55.7%, 56.7% and 57.7% relative to Shishou, respectively. Tables 2 and 4 demonstrate that Shishou has the highest EYR and the lowest ELR, which is slightly lower than Honghu's. This highlights the superior efficiency and minimal environmental impact of Shishou's RCR system, resulting in the most advantageous EISD. However, despite having the highest renewable input proportion (%R) and sustainability, Shishou's total yield (Y) of crayfish and rice is the lowest, with its total inputs (U) being second highest at 8.20×10^{16}, closely following Gong'an (8.25×10^{16}).

3.3.2. Spatial Distribution of Environmental Impact and Sustainability of RCR

As depicted in the spatial distribution map of the ELR in Figure 11, RCR systems in the Jianghan Plain feature heavier environmental loads in the north and west compared to the south and east. High environmental loads are primarily concentrated in Shayang and Gong'an in the northwest, accounting for about 31.88% of the area. Medium environmental loads are found near the eastern Hong Lake, including Qianjiang, Jianli and Honghu, covering approximately 57.79% of the area. These are regions where RCR had been previously developed. Despite the refinement of rice–crayfish rotation techniques in these areas, the substantial input of chemical fertilizers and pesticides due to long-standing cultivation habits results in notable environmental impacts. Shishou, with an ELR value of less than 0.20, represents the area with the lowest environmental load, accounting for about 10.33% of the area. These regions adopted the RCR system earlier, due to the longstanding practice of heavy fertilizer and pesticide use which contribute to environmental impacts. The area with the lowest environmental load is Shishou, with an ELR below 0.2, comprising around 10.33% of the area.

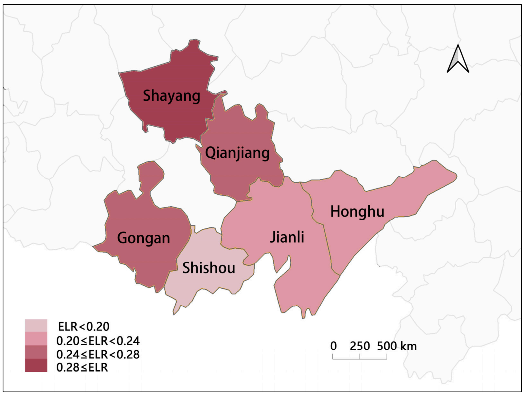

Figure 11. Spatial distribution of environmental load ratio (ELR) for RCR.

According to Figure 12, the sustainability (EISD) of RCR systems in the Jianghan Plain demonstrates a trend of higher levels in the southeast and lower in the northwest, opposite to the ELR distribution. In terms of area distribution, the sustainability of the system is mainly concentrated in regions surrounding Hong Lake, specifically encompassing Honghu and Jianli counties, which together occupy 43.28% of the total area. The medium sustainable area extends along the western coast of the Yangtze River and the south side of Chang Lake, covering approximately 30.85% and including Qianjiang and Gong'an counties. Conversely, the region with lower sustainability is situated across Chang Lake from the medium sustainability area, covering approximately 15.54% of the total. Furthermore, the most sustainable areas are found to the east of the Yangtze River in Shishou County, constituting 10.33% of the entire region.

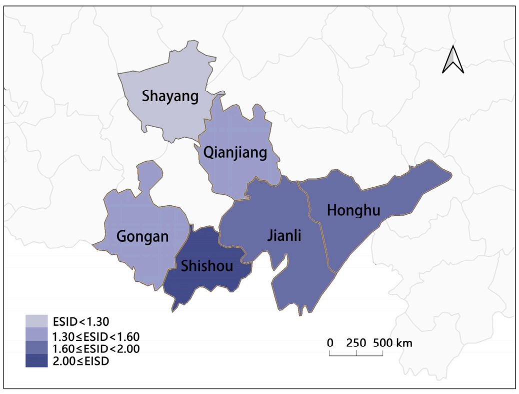

Figure 12. Spatial distribution of emergy index for sustainable development (EISD) for RCR.

4. Discussion

4.1. Performance of Resource Input

This study reveals pronounced regional variations in resource inputs within the Jianghan Plain's main areas for RCR systems. Spatially, the distribution of total resource inputs (U) shows a trend of being predominantly higher in the southern and western regions, with a decline observed toward the north and east. Additionally, the utilization of renewable resources (%R) lessens from the southeast to the northwest. These results indicate a varied reliance on natural and economic purchased resources among different regions. These findings align with those of Zhang et al. [21] in their study, which may arise from regional cultivation practices and resource management strategies. Notably, Gong'an has the highest total resource inputs, underscoring a higher dependency on both natural and economic resources compared to other counties [38]. Shishou in the south has the highest rate of renewable resource utilization, suggesting a strong dependency on renewable natural resources, chiefly due to its higher irrigation water inputs (Table 2).

Figure 3 shows that, across different regions, the allocation of resource inputs favors natural resources over socio-economic resources. Compared to rice fallow cultivation, the RCR system has reduced its dependency on natural resources while increasing demands on economic resources, but the input of natural resources remains the primary input [29,31,39]. Irrigation water plays a crucial role as a critical natural resource input, particularly because crayfish farming demands superior water quality compared to traditional rice farming. The latter involves extensive water management, including storage and regular alterations [40]. Despite the research area in Jianghan Plain, near the Yangtze River, Hong Lake and Chang Lake, where water resources are abundant, the special water needs of RCR may require additional inputs of irrigation water, including water quality management, as well as the construction and maintenance of irrigation systems [41].

Previous research has shown that economic purchased resource (F) inputs significantly affect field environments in rice-based rotation systems [22,29,42,43]. This research reveals that, in the Jianghan Plain, the five major economic purchased resources with the highest input ratios are compound fertilizers, medicines, machines and tools, compound forage and aquatic plants, whose volume and proportion vary regionally. This result supports the findings of Li [39], who noted that the RCR system increases the energy input from economically purchased resources by 28% compared to rice fallow cultivation, with significant increases in labor, crayfish feed and irrigation water [44]. Compared to the conventional rice farming system, this increase mainly arises from the greater F inputs required for the crayfish raising and rice seedling transplantation [45]. The RCR model needs crayfish forage input, but some farmers do not have enough experience with feed due to their limited years of practice, which may then result in feed wastage. Moreover, feed costs are directly linked to the crayfish growing period since most farmers align feeding with harvest times [46,47]. In addition, aquatic plants and medicines are also crucial for crayfish growth. Thus, our survey found that, due to the considerably higher price of crayfish compared to rice [40], most farmers focus on crayfish feed, not rice farming [29,48]. However, the lack of mature farming techniques among some farmers leads to crayfish diseases [49], resulting in the excessive use of medicines and aquatic plants. Furthermore, fertilizer inputs have always played a substantial role in the rice-based cultivation system. Many researches indicated a surge in fertilizer use in China since the 1980s [50].

In our study area, over fifty percent of the farmers still adhere to a conventional, resource-intensive production approach, and this practice results in excessive resource use and acts as an obstacle to maximizing ecological and economic advantages related to land use [51]. However, many studies show that RCR reduces fertilizer inputs, which aligns with the results by Zhang et al. [52], who found significant reductions in fertilizer and pesticide usage in rice–turtle co-cultivation systems with unchanged rice yields. The RCR system capitalizes on the inherent synergy between rice cultivation and crayfish feeding, resulting in improved soil physical and chemical properties and an increase in organic components [48,53,54]. Thus, it is necessary to improve water quality to make nutrients more readily absorbable by rice plants that can partially replace the compound fertilizers [55]. Moreover, the high profits of RCR may motivate farmers to optimize their inputs, including fertilizers. The increased income from the co-cultivation could lead farmers to invest in sustainable practices that reduce chemical inputs while enhancing yields. Chen et al. [29] discovered that RCR tends to reduce the reliance on compound and nitrogen fertilizers when compared to traditional rice cultivation, and it may even obviate the necessity for phosphorous fertilizers. Nevertheless, crayfish utilize only 20–30% of the nitrogen present in their feed, with the remainder often escaping into the environment [22]. Consequently, it is imperative to investigate resource utilization efficiency within this region.

4.2. Resource Utilization Efficiency

The analysis of the nutrient utilization rate of the RCR system in the main production areas of the Jianghan Plain showed regional variations in UEV and EYR. Spatially, the higher efficiency concentrates in the middle regions and decreases to the east and west, which reflect the differences in energy value conversion and resource utilization efficiencies across regions. It is worth noting that the value of UEV and EYR are not consistently aligned, which shows that areas with higher overall resource utilization rates do not necessarily exhibit higher economic resource utilization. This finding is not consistent with that of Li [39], who found that the rice–crayfish system has a higher UEV than the rice fallow system, but a lower EYR, indicating that both the total and economic resource utilization efficiency of the rice–crayfish system surpasses the rice fallow system [56]. The reason for this difference in results may be the difference in farming systems. The previous analysis in this study shows that the RCR system relies more on natural resources, so the utilization ratio of L has a greater impact on the utilization ratio of U.

Therefore, the results of F utilization efficiency in each region do not correspond to the U utilization ratio, which reveals the differences in the utilization of different types of resources regionally [57]. Notably, this study found that Shishou has the highest UEV and EYR, indicating that Shishou has the lowest total input utilization efficiency, but its utilization of F is higher [58]. This indicates that the coast of Hong Lake in the southeast, including Shishou, Honghu and Jianli counties, has lower conversion efficiency than the northwest in terms of converting input resources into usable energy, but has a higher utilization of F.

From the emergy input–output analysis presented in Table 2, Shishou has the highest U but records the lowest Y, indicating the least efficient utilization of U among the research areas. To some extent, this illustrates an oversupply of resource inputs into the RCR system of Shishou [24,26]. On the other hand, Gong’an, boasting the highest Y of 2.41×10^{17} sej, also has a relatively higher U of 8.18×10^{16} sej, making it the second highest among the counties. Moreover, its UEV is only higher than that of Qianjiang, the lowest, which exhibits a typical high input with a high output farming model [59]. Nevertheless, its EYR shows relatively low efficiency in this region, at only 3.99, suggesting an inefficient use of F in its production processes [24]. Specifically, its fertilizer consumption exceeds that of other regions by more than threefold, leading to significant wastage. In contrast, Qianjiang, with the area’s lowest UEV, maintains a moderate EYR and second-highest Y in the region at 2.30×10^{17}, indicating a balanced resource utilization. This is because Qianjiang, as the birthplace of RCR in China, has a longer development history and more mature RCR farming techniques [60]. Honghu, marked by a higher UEV and a lower EYR, shows a high utilization ratio of both U and F, but contrasts with a comparatively lower total Y within the region, at just 1.85×10^{17}. Considering the U value, this may be due to a smaller total resource inputs and a somewhat irrational unreasonable resource input structure [61].

4.3. Environmental Consequence and Sustainability

Analysis concerning the environmental consequence and sustainability demonstrates that all RCR systems in the Jianghan Plain maintain ELR values under 2 and ESI values above 1, which suggests that the system is sustainable with a minimal environmental impact (ELR < 2) [26], hence supporting the research of Hou et al. [30]. Additional evidence from our survey indicates that RCR, recognized as an environmentally friendly system, enjoys popularity among both farmers and local governments. The success of this model is rooted in a symbiotic relationship between rice and aquatic animals in one system that enhances the system’s overall efficiency due to their interactions to produce a synergistic effect [62,63]. In

RCR, paddy fields not only offer crayfish shelter, optimal water temperatures and suitable oxygen levels, but also provide them with a variety of food sources including rice grains, weeds, pests, residual seeds and soil organisms [21,29,64].

Meanwhile, the foraging and excretion activities of crayfish and other aquatic animals impact the paddy soil, water and air, thereby influencing rice growth, which improve soil permeability, reduce soil pH, increase the contents of available N, P, K and soil organic ingredients [65,66]. This behavior also improves water mixing by layers to improve solar radiation absorption and oxygen levels in the water. Additionally, crayfish contribute to weed control, aiding in the decrease in greenhouse gas emissions [49,64].

In addition, some studies found that RCR systems have a certain environmental impact on the field [22,29]. Some researchers argued that, compared to traditional rice cultivation systems, RCR in Qianjiang has a significantly higher environmental impact index [29], leading to increased resource consumption, pollutant emissions and potential toxicity, which may be underestimated in rice paddies [22]. However, when verifying the ELR values specifically, all are below 2, indicating that RCR and traditional rice cultivation systems do not exert significant environmental pressure [24], which is the same as the findings of this study. Yet, some other researchers revealed that ESI values of both systems are <1, indicating a lack of sustainability in either system [18]. Brown and Ulgiati [26] postulated that the variable agriculture conditions in different region may explain the contrasting conclusions.

Moreover, since rice field drainage is intermittent, previous studies only monitored water samples from rice fields at the end of crayfish cultivation as effluent samples, overlooking fresh water added during the production process, which potentially introduced bias [18,67]. Overall, the RCR system still has potential to reduce its environmental impact further by standardizing production, enhancing regulation and focusing on effluent treatment and discharge.

From the ELR spatial distribution map (Figure 11), it is apparent that the environmental impact of RCR in the study area decreases from northwest to southeast, while the EISD exhibits an inverse trend that declines from southeast to northwest (Figure 12). It is important to note that, while ELR and EISD values are related, they do not have a decisive influence on each other, indicating that a direct inverse relationship between ELR and EISD is not always present but does have a degree of randomness [24,26]. The analysis of the %R (Figure 6) further reveals that high %R values are concentrated in the southeast and decrease toward the northwest, in opposition to the ELR distribution. This suggests that the input of F, particularly pesticides and compound fertilizers, significantly impact the field environment [19]. The input of compound fertilizers in Gong'an, for instance, exceeds that of other areas by two to three times (Figure 7). Hence, RCR in the northwest region impacts the environment more significantly.

The reasons behind these spatial discrepancies in environmental impacts and sustainability are multifaceted, involving factors like natural environment variations, agricultural practices, farmer behaviors and government policies [23]. Zhu et al. [68] enunciated that, despite the abundance of water sources and relatively flat farmlands in the Jianghan Plain, geographic differences within the region influence resource accessibility. Also, water resources in the northwest are more abundant and accessible than in the southwest, where RCR was first adopted in the flat, water-abundant traditional rice fields and then gradually expanded to the drier, rain-fed farmlands of the same region [23].

During this transformation, some areas converted dryer and unsuitable terrains into IRC fields [11], which are not ideal for crayfish cultivation. Moreover, higher profits of crayfish partially explain the enthusiasm of farmers [69], most of whom transitioned from conventional rice cultivation to RCR. Thus, lacking experience and technology in rice–crayfish production, farmers tend to trust peers for knowledge, leading to regional differences in agricultural input. In recent years, small-scale farmers have experienced faster growth compared to larger-scale operators. The latter group, with lower education levels, often rely more on personal experience rather than formal, government-organized technical training; unfortunately, this reliance prevents the application of timely updates and the optimization of production techniques [70]. This is evident in regions like Qianjiang, the birthplace of RCR, where low EYR leads to high ELR (Figure 8). Despite the government's consistent efforts to provide technical training for rice–crayfish production, more than half of the farmers persist in using traditional, extensive production methods, resulting in severe overuse [71].

Additionally, government policies significantly influence the environmental impact and sustainability of the rice–crayfish system [29]. Jianli County, located in the southeast, has the largest area and highest yield of RCR in the region, whose government actively promotes RCR through agricultural festivals and established production protocols to regulate farmers' cultivation practices, resulting in stronger system sustainability compared to other areas [23]. In summary, standardizing agricultural input and allocating regional resources rationally are crucial for enhancing the sustainability of the RCR in the region.

4.4. Potential for Optimization of Production

Taking an aerial perspective, it is important to research methods for optimizing resource utilization in order to for enhance environmental quality in farmlands and improve rice and crayfish outputs within Jianghan Plain [31]. Analysis of resource inputs suggests that the key to improving resource efficiency lies in a better management of irrigation water, compound fertilizers, medicines, machines and tools, compound forage and aquatic plants. Moreover, considering the lower UEV of machine compared to human labor, less solar energy value is needed per unit of machine than for human labor [39]; thus, promoting mechanization is one of the effective strategies to enhance resource utilization efficiency for RCR [72].

RCR shows a considerable nitrogen surplus when compared to traditional rice farming, primarily due to the nitrogen from forage [22]. Therefore, a major reason for excessive forage input is the high farming density of crayfish [73]. Aquatic animals in rice–crayfish systems utilize only 11.1–14.2% of feed nitrogen, while rice utilizes 32%, leaving the remainder in the water and soil [74]. Numerous studies have identified a potential risk of high nitrogen and phosphorus content in water associated with RCR [75–77].

The extant literature has found that the fertilizer efficiency of RCR in the Jianghan Plain exceeds 28 kg/kg, which is higher than the current efficiency for rice fertilization in China [31]. This indicates potential for optimization in fertilizer application schedules, types and amounts based on local soil fertility during cultivation [78,79]. More so, crayfish feces could serve as a substitute for chemical fertilizers [22,30], and their foraging activity releases excrement into the fields, enhancing nutrient availability [66]. Researches have indicated that rice yields benefit from the direct use of aquatic animal waste which is rich in phosphates and ammonium nitrogen, leading to increased production [80].

Specifically, RCR can increase rice yields by 5–7% and improve fertilizer efficiency by 8% [7], and is thus adopted by the government and farmers. However, the region is predominantly composed of smallholders who rely on traditional practices and show little interest in learning new techniques, often prioritizing crayfish over rice due to its higher economic profits, leading to non-standardized cultivation practices [23]. Also, optimizing field management could reduce the reliance on chemical inputs, improve crop yields and reduce environmental impacts, while fostering sustainable regional development [81]. The rice–crayfish model also demands more irrigation and water changes, heightening the risk of agricultural diffuse pollution.

Research on rice–crayfish co-culture systems found that systems with lower carp densities not only maintained economic benefits but also significantly reduced water phosphorus and ammonium contents, reducing pollution risks [54,82]. Thus, regulating crayfish stocking densities in paddy fields emerges as an essential step toward minimizing non-point source pollution in RCR. Moreover, substituting crayfish feed with aquatic plants has been shown to enhance system sustainability significantly, owing to the photosynthetic reduction in CO_2 contents and improvement in water quality [12,39]. Accordingly, the rational planting of aquatic plants can enhance the sustainability of RCR and alleviate environmental pressures.

Overall, for the southeast region, it is essential to leverage its abundant natural resources, promoting the scale and standard production of RCR. While ensuring ecological preservation, moderately increasing economic purchased investments can enhance production competitiveness. Diversifying business models and strengthening farmer training can facilitate the transformation and upgrade of the rice–crayfish industry and sustain rural economic growth. For the northwest region, balancing economic development with environmental protection and sustainability is crucial. This involves reducing unnecessary resource inputs, enhancing resource utilization efficiency and minimizing environmental impact. Thus, intensifying environmental awareness and technical training can also elevate farmers' ecological consciousness and skill levels. The government has the opportunity to promote the industry chain and elevate product value by executing the "Three Products and One Standard" action plan. This initiative focuses on pollution-free agricultural products, green food, organic agricultural products and geographical indications. By doing so, it contributes to the robust growth of the integrated rice–crayfish cultivation industry.

5. Conclusions

This study employs emergy analysis to conduct a comprehensive examination of the rice–crayfish rotation (RCR) systems in the main production areas of Jianghan Plain, including analyses of resource inputs, resource utilization efficiency, environmental impacts and sustainability assessments. It delves into the development discrepancies and spatial distribution characteristics of the RCR systems across various regions. Our study reveals that, in the RCR systems of Jianghan Plain, total resource input analysis reveals a higher total investment in the southern regions, such as Gong'an County, which reaches 8.25×10^{16} sej—28% higher than the northern Shayang County. This indicates a substantial demand for natural and purchased resources in southern agricultural production. Notably, Shishou County boasts the highest %R at 84.34%, compared to the lowest in Shayang County at 78.38%, suggesting superior sustainable resource management in Shishou and a reliance on non-renewable resources like medicine and fertilizers in Shayang. Moreover, while Shishou shows high efficiency in the utilization of economically purchased resources, as indicated by its high UEV and EYR values, its total resource utilization efficiency is the lowest. In contrast, the northern region of Qianjiang exhibits the highest total resource utilization efficiency, with the lowest UEV value at 0.31. Additionally, the distribution of environmental impacts and system sustainability reveals that the southeastern area, like Shishou County, experiences the lowest environmental load with an ELR of 0.19. Whereas the northwestern area, such as Shayang County, faces substantial environmental pressures, with its ELR being 1.5 times that of Shishou and with an EISD of only 1.27. These findings underscore the differences in agricultural practices and resource management strategies across regions, as well as their significant implications for sustainability and environmental impact.

Based on the conclusions above, the following policy recommendations could be proposed:

(1) For the southeastern regions, efforts should continue to leverage the advantage of abundant natural resources by promoting the scale and technical standardization of RCR. At the same time, with a commitment to ecological conservation, an increase in socio-economic investment should be considered to enhance competitiveness. By developing business models such as "companies + farmers", strengthening technical training for farmers and upgrading the rice–crayfish industry, sustained growth in rural economies can be encouraged.

(2) In the northwestern regions, while ensuring economic development, emphasis should be placed on environmental protection and sustainable growth. It is essential to reduce unnecessary inputs and enhance resource efficiency for lower environmental loads. Strengthening environmental awareness and technical training among farmers will help raise their awareness and skills related to environmental protection. Strategies

such as extending the RCR industry chain and enhancing product value should be implemented to promote the healthy development of the RCR industry.

(3) Governments should increase support for RCR through relevant policies and measures to encourage the industry's healthy development. Strengthening inter-regional cooperation and exchanging resources and technology can significantly enhance synergistic growth across industries. Additionally, establishing and maintaining an environmental assessment mechanism is crucial. Regular environmental assessments of RCR should be conducted to ensure that industry development is in harmony with environmental conservation.

Theoretically, this contributes to adding to the emergy analysis research for RCR, facilitating studies on the spatial disparities and imbalances in environmental impacts at a macro-spatial scale. Practically, this research offers a macro-spatial perspective that is crucial for the strategic allocation of agricultural resources and optimizing regional agricultural layouts, significantly benefiting the development of the RCR industry based on local conditions.

Finally, here are some limitations and prospects for this study: firstly, the data for this research randomly came from surveys of farmers in the field, capturing only the actual inputs of agricultural resources. However, variations in brands of agricultural supplies and types of machinery across different farms were not quantitatively assessed in these types of studies. Future agriculture could develop an intelligent system for tracking agricultural input on each farm, facilitating a detailed analysis of these variations. Secondly, while this study focuses on the current development of RCR systems and offers related policy recommendations and spatial management strategies, future research could explore the willingness and motivations of farmers to adopt new agricultural practices. This may further advance the optimization of regional development of RCR systems.

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