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Emergy-Based Sustainability Evaluation of the Mulberry-Dyke and Fish-Pond System on the South Bank of Taihu Lake, China

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Abstract: The Taihu Lake drainage basin is the birthplace of the Mulberry-dyke and Fish-pond System (MFS), a traditional eco-agricultural system. In 2017, the largest and best-preserved "Zhejiang Huzhou Mulberry-dyke and Fish-pond System" located by the South Bank of Taihu Lake, China was recognized as Globally Important Agricultural Heritage Systems (GIAHS) by the Food and Agriculture Organization of the United Nations (FAO), and its value has been appreciated. As a dynamic heritage, the sustainable development of MFS is a fundamental requirement of the conservation of GIAHS. In this regard, it is necessary to figure out an approach to evaluating the status of its sustainable development. This paper analyzes and contrasts the emergy embodied in the three patterns of MFS over different periods, then constructs an index system of sustainability evaluation involving the production and consumption processes based on that. Finally, it provides the evaluation and analysis. The three patterns of MFS differ in the system structure. In the Ming and Qing Dynasties (abbreviated as Ming-Qing pattern), MFS was an integrated system compromised of mulberry cultivation, silkworm breeding, fish breeding, and sheep breeding, while other patterns exclude sheep breeding, but increase the input of fertilizer, and add the production of mulberry-leaf tea and other local specialties. The results show that the MFS in the Ming-Qing pattern has the highest integrated evaluation index of sustainable development, followed by the traditional MFS pattern and the new MFS pattern employed nowadays. This indicates that the current capability of sustainable development has decreased compared to that in the Ming and Qing Dynasties. The integrated evaluation index regarding the consumption process of the new MFS pattern is higher than the traditional one, suggesting that it needs to promote sustainability in the production process, especially via the utilization rates of renewable resources and wastes.

Keywords: mulberry-dyke and fish-pond system; globally important agricultural heritage systems; emergy; sustainability; evaluation

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1. Introduction

The Mulberry-dyke and Fish-pond System is a comprehensive and multi-dimensional eco-agricultural system promoted by farmers in the Taihu Lake drainage basin and Pearl River basin, China under specific historical conditions, significantly impacting ancient and modern agriculture [1,2]. Shen's Agricultural Book, "Bunongshu" (an agricultural book written by Lvxiang Zhang in Qing Dynasty), a New Account of Guangdong, Humble Opinions about Sericulture in Middle Guangdong and some other ancient works of literature made detailed records and analysis of MFS [3,4]. In 1958, Gongfu Zhong, affiliated with Guangzhou Institute of Geography (GIG), published the first academic paper specifically demonstrating MFS [5]. Following that, some agricultural planning departments in China began to regard the dyke-pond systems, represented by MFS, as an agricultural model. Since 1980, GIG has launched the project Systematic Research on the Land-Water Interactions in the Dyke-pond Area in the Pearl River Delta (1980–1983) to comprehensively study the dyke-pond systems, which was funded by United Nations University (UNU). Thus began the widespread concerns and popularization of MFS. Influenced by the development of large-scale agriculture and restructuring of regional industry, MFS in both Taihu Lake drainage basin and Pearl River delta has experienced decomposition and shrinkage since the 21st century [6]. In 2005, FAO launched the initiative "conservation and adaptive management of Globally Important Agricultural Heritage Systems (GIAHS)", collaborating with international organizations and countries with the support of the Global Environment Fund (GEF). This project is aimed at enhancing awareness of local farmers and minorities' traditional knowledge and management experience concerning nature and environment in a global range, and further tackling the challenges faced by rural and agricultural development [7]. It was against this background that MFS featured by the closed eco-cycle, in which mulberry leaves are fed to beneficial worms, worm feces is fed to fish, and fish feces is used as fertilizer for mulberry trees, was revalued and recognized as a marsh-utilizing method and an efficient traditional eco-agricultural mode with unique creativity. Along with these contributions, Zhejiang Huzhou Mulberry-dyke and Fish-pond System and Guangdong Foshan Dyke-Pond System succeeded in applying for GIAHS and China Nationally Important Agricultural Heritage Systems (China-NIAHS) in 2017 and 2019, respectively.

The key vision of dynamic conservation of GIAHS is improving the sustainability of agriculture, ecology, and traditional society [8]. Thus, an urgent assessment regarding the sustainable development of MFS is necessary. Since the late 1980s, scholars have begun research on the effects on the dyke-pond systems brought by the changes of the external environment after the Chinese Economic Reform. For instance, the application of remote sensing in research has raised people's awareness of the temporal and spatial variations of the dyke-pond systems and the development of "high-yield, high-quality and high-return" agriculture has significantly reduced land-water interactions [9–11]. Also, Korn (1996) argues that the rapid development of the economy has led to a disregard of the ecological environment and traditional agricultural techniques [12]. Based on the analysis of the dyke-pond systems and the causes behind this, Nie et al., (2003) and Li et al., (2005) hold the view that monocropping and agricultural non-point source pollution are highly associated with the degradation of dyke-pond systems and suggest a new approach to ecological recovery and system restructuring [13,14]. Li et al. (2007) provide evidence for sustainable land use and relative policy-making by establishing the evaluation index system regarding the ecological environment quality of the dyke-pond systems [15]. After being selected as an important agricultural cultural heritage, the conservation and development of MFS have attracted more attention from academia, and research has covered the assessment of MFS service value, emergy analysis, input-and output efficiency analysis, macro and micro analysis of evolution process, adaptive protection and management countermeasures [6,16–19]. Among these studies, the emergy analysis emphasizes the integrated sustainability evaluation about MFS from the economic and ecological perspectives, which is a highly scientific and practicable quantitative assessment method. Emergy is a concept developed in response to the intrinsic differences between different categories or sources of energy. This refers to the amount of one kind of flowing or stored energy contained in another kind of energy. Nonetheless, the influence of the consumption process on MFS sustainability is overlooked when setting the integrated evaluation indices.

In order to evaluate the sustainability of MFS, it is necessary to collect relevant data from the historical dimension and improve the evaluation method. We first define three kinds of MFS patterns: the first is Ming-Qing pattern, which reflects the production situation of MFS in Tiahu Lake area (located in the south bank of Taihu Lake) in the 16th and 17th centuries; the second is the traditional pattern, which represents the current production status of MFS under the protection of agricultural heritage system; and the third is the new pattern, the innovative cultivation and breeding pattern typically adopted by Nanxun Yunhao family farm, indicates the possible development direction of MFS in the future. Then, this paper investigates the emergy of three MFS patterns by the South Bank of Taihu Lake over different periods and constructs an index system of sustainability evaluation involving the production and consumption processes based on that. Then, through the calculation of entropy and analysis of results, we carry out a comprehensive evaluation of the sustainability performance of MFS by the South Bank of Taihu Lake. We assume that the sustainability of MFS has been undermined with the development of agricultural technology. That means the sustainability of the Ming-Qing Pattern, the Traditional Pattern, and the New Pattern rank from high to low.

2. Overview of the Study Area

Located in northern Zhejiang Province, China, the area of the South Bank of Taihu Lake is dominated by Hangjiahu Plain, which has a dense water network. The average density of the rivers reaches 12.7 km/km^2, the highest in China (Figure 1). In ancient times, it belonged to the Great Five Lakes around Taihu Lake group of Ancient Ling Lake group and Ancient Dianmao Lake group, which was a year-round water-accumulating low-lying wetland. During the Spring and Autumn Period, states of Wu and Yue launched an arms race to counterbalance each other in the Taihu drainage basin, and collaboratively undertook a large-scale water conservancy project, the Lougangweitian System (The system successfully separated soil and water and provided favorable conditions for agricultural production). The South Bank of Taihu Lake is one of the birthplaces of some agricultural production techniques, such as the cultivation of mulberry trees, silk breeding and fish cultivation, which can be supported by further evidence. The silk fabric unearthed at the Qianshanyang site in Huzhou was measured 4715 $\pm$ 100 years ago and was identified as an artificial silk fabric by Zhejiang Textile Sciences Research Institute, proving that the South Bank of Taihu Lake is one of the origins of artificial silkworm breeding. Besides, according to Wu-Yue Chunqiu and other pieces of literature, Minister of State Yue, Fan Li implemented a policy of fish cultivation to strengthen State Yue in the South Bank of Taihu Lake. Later, people wrote the Tao Zhu Gong Fishing Book based on Fan's fish cultivation technique, the earliest book devoted to fish cultivation in the world. It also could be inferred that the Pond-Fishing Mode appeared in the South Bank of Taihu Lake about 2500 years ago, according to Fan Li's life years.

Figure 1. Geographical Location of GIAHS "Zhejiang Huzhou Mulberry-dyke and Fish-pond System".

Tracing back history, the cultivation of mulberry trees, silk breeding and fish cultivation and the Lougangweitian System provides a prerequisite for the formation of MFS. Research shows that the formation of MFS by the South Bank of Taihu Lake should be no later than the middle and late Tang Dynasty, and then was perfected in the Song Dynasty, flourished in the Ming and Qing Dynasties [20]. Today, there are still 40 km^2 of mulberry land and 100 km^2 of fish pond preserved by the South Bank of Taihu Lake, which is the most concentrated area of the largest scale traditional MFS. Zhejiang Huzhou Mulberry-dyke and Fish-pond System, located by the South Bank of Taihu Lake was added to the China-NIAHS list in 2014 and recognized as a site of GIAHS in 2017.

As an agricultural heritage system identified to be a GIAHS site, the traditional MFS is verified with its endangered status of serious degradation and shrinkage at both macro and micro levels. At the macro level, the South Bank of Taihu Lake is located in Eastern China, a developed area with a high level of agricultural modernization, where the large-scale production in the aquaculture industry and the regional transfer to Western China of silkworm industry drive the discomposure of MFS. At the micro-level, the economic benefits of traditional MFS tend to be lower, challenged by the specialized large-scale production of modern agriculture, so a substantial group of farmers have already abandoned the traditional pattern based on rational considerations. Although the factors above resulted in the degradation and shrinkage of MFS, we cannot underestimate its significance. As a GIAHS site, Zhejiang Huzhou Mulberry-dyke and Fish-pond System represents a harmonious and balanced agriculture pattern derived from the long-term integration of production, life, and nature. Li also suggests that it not only preserves a remarkable agricultural landscape for modern and efficient eco-agriculture, restores a sustainable ecosystem, spreads valuable traditional knowledge and culture, but also contributes to the conservation of agricultural biodiversity [21]. In recent years, the government of the city of Huzhou and Nanxun District have taken measures to preserve MFS, which generated positive effects but showed the limitation of preservation area, adaptability of promotion, and sustainability of development.

3. Methods

3.1. Emergy Analysis Procedures of MFS

The emergy theory and corresponding accounting method were created from deep research on energy transformation and the energy hierarchy by H. T. Odum and other American ecologists. Odum (1996) defines emergy as one kind of available energy previously consumed in a production process embodied in another kind of flowing or stored energy [22]. It is a kind of embodied energy, in essence, providing a standardized measure for the environment, resources, labor, commodity, currency, and even information involving energy in nature and human society, so it is regarded as a connection between ecology and economy [23]. Emergy transformity is also called unit emergy values (UEVs), representing the amount of emergy needed to generate one unit of product or service, and it is used for calculating the energy of different hierarchies [24–29]. As most kinds of energy in ecological-economic systems are from solar energy originally, solar emergy is generally applied for measuring emergy embodied in any system and solar transformity is commonly used to express emergy transformity. The emergy baseline is estimated by accumulating the annual emergy absorbed in the global eco-system. It is noteworthy that the emergy baseline is a reference standard for calculating a diversity of emergy transformities, so these transformities should be adjusted according to the update of the emergy baseline. Since H. T. Odum (2000) first calculated the emergy baseline (9.44×10^{24} sej/yr), Odum and other scholars have recalculated the baseline three times [25,30,31]. In this research, the emergy baseline of 12.00×10^{24} sej/yr determined in 2016 is employed for the emergy analysis.

According to the main steps of conducting the emergy analysis on one ecological-economic system, the analysis on the input-output status of three patterns of MFS over different periods by the South Bank of Taihu Lake is synthesized as follows: first, collecting basic data including the value of the input resources, output products and overall outputs, conversion coefficients and solar transformities respectively, then calculating the emergy/money ratio (EMR) of Huzhou based on the emergy analysis of the ecological-economic system in Huzhou, which is expressed with the unit sej/¥; second, classifying the aforementioned flows in the three patterns of MFS individually and converting the material, energy, value, etc., in the system into a unified metric, the solar emergy, through the UEVs and the EMR in Huzhou and drawing an emergy analysis table; third, identifying the boundary of each system and drawing the emergy system diagram separately according to the structures and flows of pure energy, materials and currency; finally, selecting some emergy indicators, including emergy self-sufficient ratio (ESR), environmental load ratio (ELR), emergy yield ratio (EYR) and emergy sustainability index (ESI), etc., to evaluate its sustainability performance from an integrated perspective.

3.2. Analysis Framework and Index System of MFS

In the emergy analysis, indicators assessing the sustainability performance of MFS is mainly calculated by adding the inputs and subtracting the outputs of the emergy in the "energy flow" within the production process. Generally, that involved in the "value flow" within the consumption process, including the resource input from the economic system and the products sold on the market, is ignored. MFS is operated by the farmers, whose participation is largely influenced by the cost-benefit relationship, so the sustainability evaluation about MFS is expected to cover the production and consumption processes. The emergy flows diagrams can exhibit the close relationship between the production and consumption processes in each MFS pattern. Thus, by exploring the systems from the term "flows", ecological-economic models can be built to provide an analytical framework for the construction of an index system of sustainability evaluation about MFS.

As is shown in Figure 2, the energy system consisting of energy flows involving input, reuse and output in the production process is integrated with the value system comprised of value flows from the market trading and capital management through "transformities". In such a system, neither the emergy analysis focusing on the emergy indices nor the value analysis based on cost-benefit analysis can independently give a comprehensive evaluation on the sustainability performance of MFS, and they cannot replace each other. Thus, to apply the method into the evaluation effectively, UEVs and EMR are used to transform the energy flows and the value flows into the emergy flows, quantitatively describing the operation processes within MFS and providing the measurement basis for the sustainability evaluation on MFS.

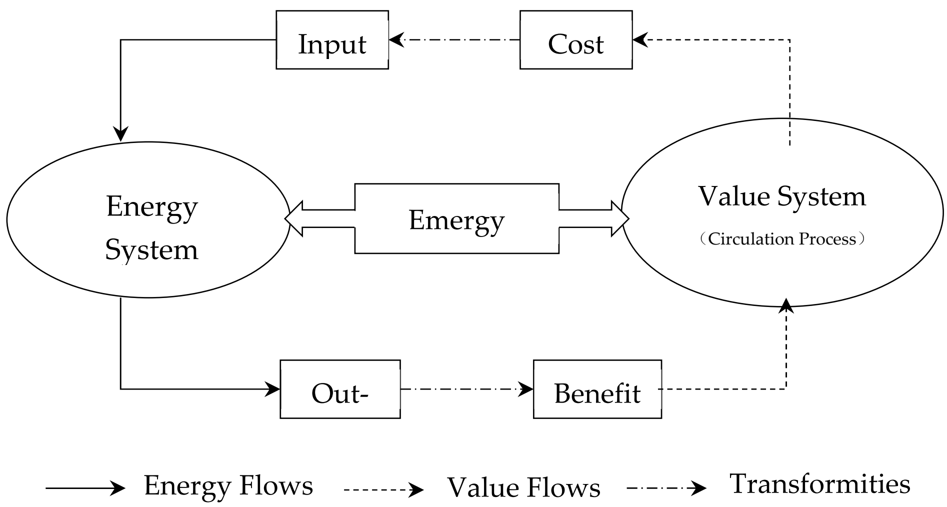

Figure 2. Energy Flows, Value Flows and Transformities in Ecological-economic Systems.

The following four aspects are considered for constructing the sustainability evaluation index system depending on the emergy analysis of MFS and the ecological-economic model: first, the structures, functions and metabolism process of MFS; second, the input structure, recycling and reuse of waste within the production process; third, the cost-benefit relationship and the capability of providing feedback and support within the consumption process; finally, the availability of the emergy evaluation indicators. Given these components, the evaluation index system shown in Table 1 is formed by following the principles of science, systematicity, relevance and operability, and drawing on the thinking of hierarchical analysis.

Table 1. Emergy-based Sustainability Evaluation Index System of MFS.

First-Ranked Target	Second-Ranked Target	First-Level Indicator	Second-Level Indicator	Direction of Effects
Sustainability Evaluation about MFS	Sustainability Evaluation on the Production Process (Energy System)	Emergy of Renewable Resources (A)	Emergy of Natural Resources (A1) Emergy of Seedling and Fry (A2) Emergy of Labor (A3) Emergy of Other Renewable Resources (A4)	Positive
		Emergy of Recycled Resources (B)	Emergy of Mulberry Leaves (B1) Emergy of Silkworm Guano (B2) Emergy of Pond Mud (B3) Emergy of Other Recycled Resources (B4)	
		Emergy of Non-renewable Resources (C)	Emergy of Fossil Energy (C1) Emergy of Pesticides (C2) Emergy of Fertilizers (C3) Emergy of Synthetic Feeds (C4) Emergy of Other Non-renewable Resources (C5)	Negative
	Sustainability Evaluation on the Consumption Process (Value System)	Emergy of Profits from Output (D)	Emergy of Profits from Silkworm and Mulberry Products (D1) Emergy of Profits from Aquatic Products (D2) Emergy of Profits from Products (D3)	Positive
		Emergy of Costs in Input (E)	Emergy of Labor Costs (E1) Emergy of Seedling and Fry Costs (E2) Emergy of Feeds Costs (E3) Emergy of Energy Costs (E4) Emergy of Other Costs (E5)	Negative

The production and consumption processes are essential to the decision-making on the development and management of MFS, so the sustainability evaluation is divided into two sections targeting at each process respectively. The former section assesses the resource input, recycling, and reuse of wastes with the first-level indicators, including the emergy of renewable resources, recycled resources, and non-renewable resources while the latter one focuses on the output feedback based on the input reflected by the market values with the emergy embodied in the costs and profits. It is illustrated that the evaluation of the production process excludes the input-output relationship because farmers usually manage production according to market values. In this evaluation index system, common items shared by all the patterns of MFS are listed in the second-level indicators, and other specific items are labeled by A4, B4, C5, D3 and E5. What is notable is that the increase in the emergy of different items has different directions of effects on the sustainability of MFS: the emergy of renewable resources, recycled resources and profits generated from output all cause effects in a positive direction, whereas the others cause effects in a negative direction.

3.3. Calculation Method of Indicators in the Sustainability Evaluation about MFS

To reflect the sustainability performance of MFS, it is necessary to quantify and integrate the multi-dimensional information in the evaluation index system, in which the assignment of weights to indicators is of great significance. In the entropy method, a well-developed method with reliable calculation steps, the value mainly depends on the amount of information that is presented, which is more objective and scientific. Combining the entropy method with the emergy-based sustainability evaluation index system of MFS, the calculations were processed as below:

(1) Construct the original data matrix E of the evaluation indicators.

Assume there are m evaluation indicators and n evaluation objects. For indicator i, the value is implied as E_{ij}, among which i = 1, 2, ... , m; j = 1, ... , n. The original data matrix could be presented as:

$$E = \begin{bmatrix} E_{11} & \cdots & E_{1n} \\ \vdots & \ddots & \vdots \\ E_{m1} & \cdots & E_{mn} \end{bmatrix}$$

In the emergy-based sustainability evaluation index system of MFS, all indicators are emergy with uniform units, so de-quantization is not required.

(2) Calculate P_{ij}, the specific weight to the evaluation object j for indicator i, among which $0 \leq P_{ij} \leq 1$.

$$P_{ij} = E_{ij} / \sum_{j=1}^{n} E_{ij}$$

(3) Calculate the entropy e_i of each indicator.

$$e_i = -\frac{1}{\ln(n)} \sum_{j=1}^{n} p_{ij} \cdot \ln p_{ij}$$

When $p_{ij} = 0$, $p_{ij} \cdot \ln p_{ij} = 0$.

(4) Calculate the coefficient of variation d_i of each indicator.

$$d_i = 1 - e_i$$

The coefficient of variation d_i is proportional to the weight of the indicator, which means, the larger the d_i, the more information the indicator provides and the greater the weight should be assigned.

(5) Determine the weight W_i to each indicator.

$$W_i = d_i / \sum_{i=1}^{m} d_i$$

$$0 \leq W_i \leq 1, \sum W_i = 1.$$

Calculate the weights according to the entropy method and perform the weighted summation of the raw data of the indicators, then the integrated sustainability evaluation index of MFS can be generated.

The calculation formula is shown as below:

$$G_j = \sum_{i=1}^{n} E_{ij} \cdot W_i$$

In this formula, E_{ij} includes the directions of effects of the corresponding indicators; G_j is the integrated sustainability evaluation index of the evaluation object j, and the greater the G_j is, the more sustainably the system performs.

4. Data

4.1. Three Patterns of MFS over Different Periods

The raw data needed for the emergy analysis includes the inputs and outputs, cost and benefits that occurred in the Ming-Qing pattern, the present traditional pattern, and the new pattern of MFS (Table 2). The data was gathered from the paper Intertemporal Analysis on Input-Output Efficiency of the Mulberry-Dyke and Fish-Pond by the South

Bank of Taihu Lake issued by Gu et al. [6]. And the details can be found in Tables 3–5 and 9 in this paper.

Table 2. Status of three patterns of MFS by the South Bank of Taihu Lake over Different Periods.

Pattern	Period	Area	Agricultural Production Methods	Source of Raw Data
Ming-Qing Pattern of MFS	Late Ming and Early Qing Dynasties	Hangjiahu Plain	Mulberry Cultivation, Silkworm Breeding, Fish Cultivation and Sheep Breeding	Records from the Agricultural Books in the 16th and 17th Century
Traditional Pattern of MFS	Contemporary Period	Huzhou MFS Agricultural Heritage Preservation Area	Mulberry Cultivation, Silkworm Breeding and Fish Cultivation	Survey to Farmers and Interviews with Experts
New Pattern of MFS	Contemporary Period	Nanxun Yunhao Family Farm	Mulberry Cultivation, Silkworm Breeding, Fish Cultivation	Survey to Farmers

There were many agricultural books in the Ming and Qing Dynasties in China, among which Jiean's Essays written in the 16th Century, Shen's Agricultural Book and "Bunongshu" written in the 17th Century made a detailed record of the production of rice, mulberry, silkworm, fish, and sheep by the South Bank of Taihu Lake [32]. Many scholars did further research on the development of ecological agriculture and input-output performance at that time based on these historical records. On the foundation of previous studies, this paper collected the relevant data, calculated and classified the costs and benefits of mulberry cultivation, sericulture, fish and sheep breeding and their combination with MFS by the South Bank of Taihu Lake in the Ming and Qing dynasties. Currently, the data regarding inputs and outputs, costs, and benefits occurring in the traditional pattern and the new pattern of MFS are derived from the farmers surveyed in the GIAHS preservation area "Zhejiang Huzhou Mulberry-dyke and Fish-pond System". Among them, the Nanxun Yunhao family farm adopted a water circulation system in the fish pond and a large-scale mechanized mulberry-sericulture, which achieves the recycling of wastes and increase of economic income, typically representing the new pattern of MFS.

4.2. Energy Conversion Factor and UEV

Energy from sunlight, wind and rainwater are indispensable natural resources for all the patterns of MFS. The calculation methods and references for data are exhibited in Table 3.

Table 3. Calculation Methods and References for data of Some Natural Resources.

Item of Resources	Calculation Formula	Relevant Indicator	Reference Value	Reference for Data
Sunlight	The land area of the system × Annual average solar radiation × (1-Albedo)	Annual average solar radiation Albedo	4.46×10^9 J/m^2/yr 0.3	Reference [33]
Wind	Land area of the system × Air Density × Resistance Factor × (Annual average wind speed ÷ 0.6)^3 × Wind speed gradient	Air Density Resistance Factor Annual average wind speed Wind speed gradient	1.29 kg/m^3 1.00×10^{-3} 2.7 m/s/yr 3.15×10^{7s}/yr	Reference [22] Reference [34] Reference [22]
Rain, chemical	The land area of the system × Average annual rainfall × Rainfall Density × Gibbs Free Energy	Average annual rainfall Rainfall Density Gibbs Free Energy	1.55 m/yr 1.00×10^3 kg/m^3 4.94×10^3 J/kg	Reference [22]
Rain, geopotential	Land area of the system × Average annual rainfall × Rainfall Density × Average Height × Gravitational Acceleration	Average Height Gravitational Acceleration	2000 m 9.8 m/s^2	Reference [33]

The conversion of energy (material) from the three patterns of MFS needs energy conversion factors and UEVs. Based on relevant studies, we classified and listed the reference values and their sources in Table 4.

Table 4. Reference Values and Data Sources of Energy Conversion Factors and UEVs of Relevant Items.

Item of Resources	Energy Conversion Factor	Units	Reference for Data	UEV	Units	Reference for UEV	Adjustment Factor
Sunlight				1.00×10^0	sej/J	By Definition	1.00
Wind				1.50×10^3	sej/J	Reference [22]	1.27
Rain, chemical				1.80×10^4	sej/J	Reference [22]	1.27
Rain, geopotential				1.00×10^4	sej/J	Reference [22]	1.27
Fish	6.29×10^6	J/kg	Reference [35]	2.00×10^6	sej/J	Reference [22]	1.27
Shrimp	5.18×10^6	J/kg	Reference [35]	1.30×10^7	sej/J	Reference [22]	1.27
Grass	3.00×10^6	J/kg	Reference [35]	6.83×10^3	sej/J	Reference [36]	0.79
River Snails	4.45×10^6	J/kg	Reference [35]	2.00×10^6	sej/J	Reference [22]	1.27
Feed				2.64×10^9	sej/g	Reference [37]	0.76
Mulberry Leaves	1.59×10^7	J/kg	Reference [35]	2.40×10^4	sej/J	Reference [38]	1.27
Fertilizer				3.80×10^9	sej/g	Reference [23]	1.27
Firewood	1.42×10^7	J/kg	Reference [39]	6.83×10^3	sej/J	Reference [36]	0.79
Sheep Manure				2.70×10^6	sej/g	Reference [22]	1.27
Pond Mud	3.24×10^6	J/kg	Reference [35]	3.51×10^3	sej/J	Reference [22]	1.27
Silkworm Carbon	2.09×10^7	J/kg	Reference [35]	1.06×10^4	sej/J	Reference [23]	1.27
fish Faeces	3.66×10^6	J/kg	Reference [35]	1.80×10^6	sej/J	Reference [22]	1.27
Silkworm Chrysalis	1.47×10^6	J/kg	Reference [38]	2.00×10^6	sej/J	Reference [38]	1.27
Silkworm Guano	3.66×10^6	J/kg	Reference [35]	2.00×10^4	sej/J	Deduced from Silkworm Cocoon	1.27
Silkworm Cocoon	7.64×10^6	J/kg	Reference [40]	2.70×10^4	sej/J	Reference [38]	1.27
Silk	6.02×10^6	J/kg	Reference [38]	3.40×10^6	sej/j	Reference [22]	1.27
Sheep	1.41×10^7	J/kg	Reference [33]	2.00×10^6	sej/J	Reference [23]	1.27
Wool	2.00×10^7	J/kg	Reference [40]	4.40×10^6	sej/J	Reference [23]	1.27
Labor	2.12×10^6	J/man-day	Reference [37]	7.38×10^6	sej/J	Reference [41]	0.76
Electricity				1.60×10^5	sej/J	Reference [23]	1.27

Note: The adjustment factors of UEVs were calculated based on different emergy baselines.

5. Results

5.1. Intertemporal Emergy Analysis and Comparison of Three Patterns of MFS

Through the input-output analysis and the emergy conversion, the emergy analysis table and emergy flows diagrams (Figures 3–5) can be drawn in terms of three patterns. The Ming-Qing Pattern of MFS includes mulberry breeding, pond fish breeding, and Hu sheep breeding. Most of the external resources invested in the system are renewable resources, and silkworm carbon is the non-renewable resource. The silkworm carbon and seedlings were all purchased from the market, some of the feed was collected from the natural environment, and the rest was purchased from the market. Within the system, the recycling system formed by the combination of three kinds of production greatly reduces the external resource input to the system. Almost all the mulberry fertilizer comes from the waste of silkworm, fish and sheep, and the output of the system includes silk, lamb, wool, and fish. The traditional pattern of MFS and new pattern of MFS include mulberry planting and sericulture and pond fish farming. The two patterns continue the ecological cycle system between sericulture, aquatic products, and ponds. Renewable natural resources invested include solar energy, wind energy, rainwater potential energy, and rainwater chemical energy. The resources fed back by the economy and society to the MFS include seedlings, fertilizers, feed, drugs, tools, facilities, labor, and energy. In the traditional pattern, the labor is provided by the farmers themselves, and the rest of the feedback resources are purchased from the market. In the new pattern, all the resources from the economy and society are purchased from the market. The waste of mulberry leaves, silkworms, and fish is recycled in the system. Compared with the traditional pattern, the new pattern increases the processing and production of mulberry leaves and enriches the types of agricultural products available for market circulation. However, it is in the experimental stage, and thus the sericulture link is not perfect, and the farm does not directly export to the market.

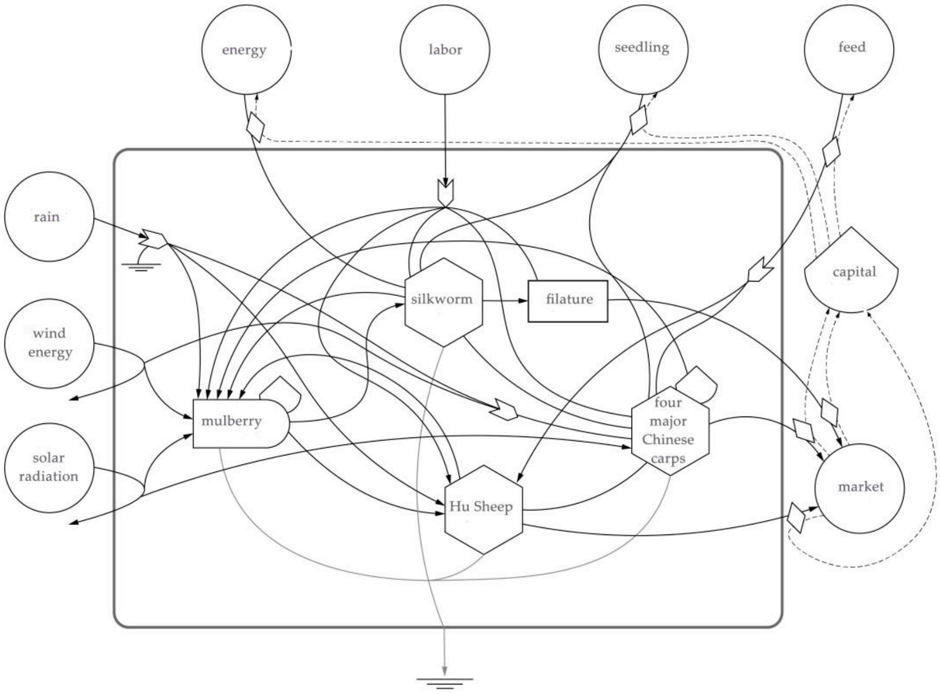

Figure 3. Emergy Flows Diagram of the Ming-Qing Pattern of MFS.

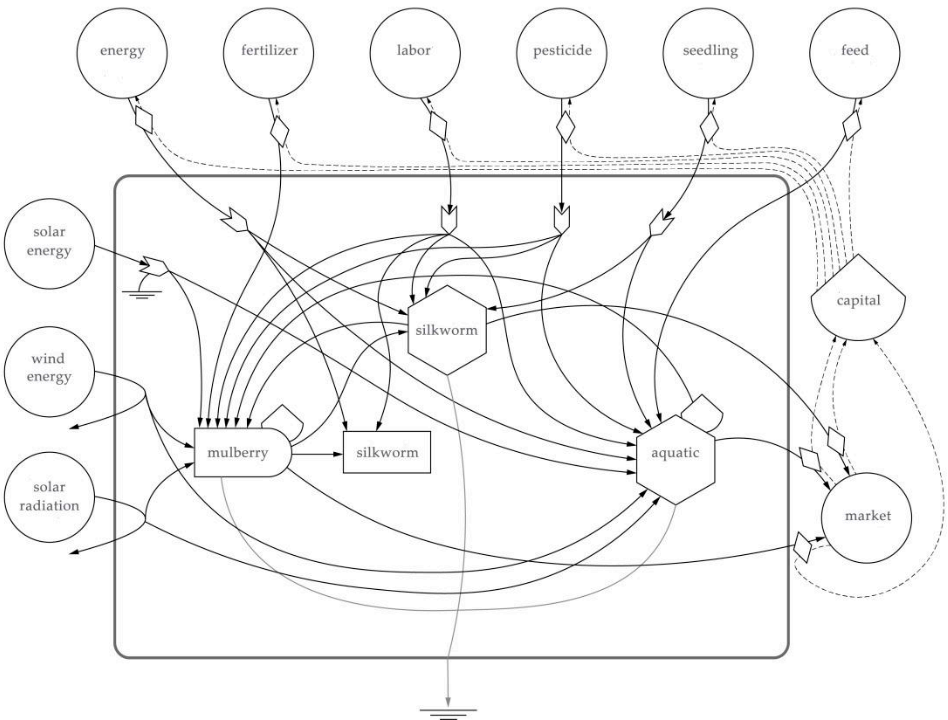

Figure 4. Emergy Flows Diagram of the Traditional Pattern of MFS.

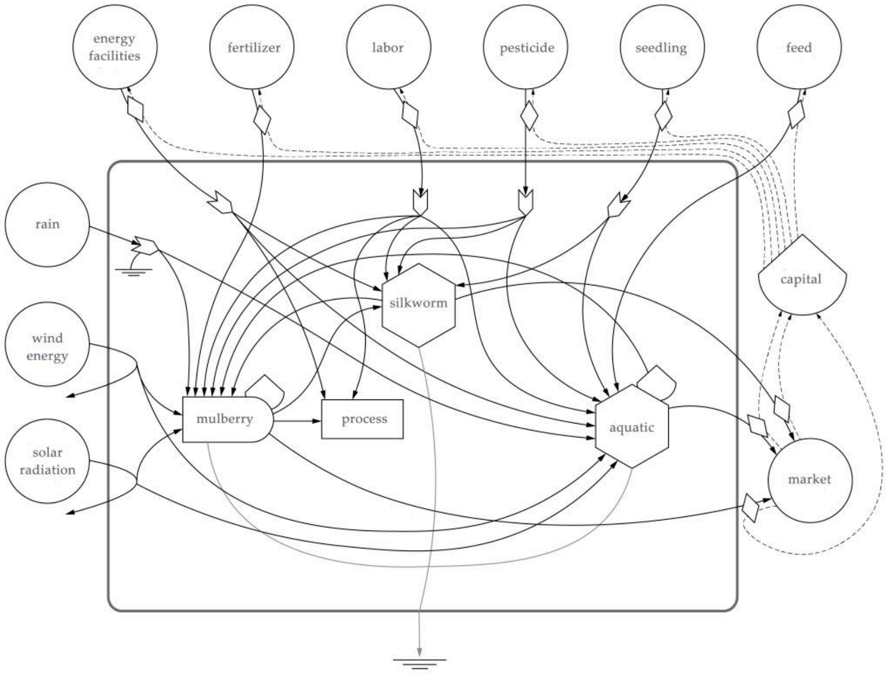

Figure 5. Emergy Flows Diagram of the New Pattern of MFS.

Table 5 describes the emergy of different categories in these patterns, which was calculated based on the emergy analysis table and contributed to further comparison and analysis of their emergy structures. It can be seen that the recycling and renewable resources exist in all three systems without any input of non-renewable resources, directly proving the MFS as a functioning cyclical model.

Table 5. Emergy Comparison of Different Categories in MFS.

Item	Ming-Qing Pattern	Traditional Pattern	New Pattern
The Input of Renewable Resources from Nature (IR)	1.02×10^{16}	2.67×10^{15}	2.71×10^{16}
Input of Non-renewable Resources from Nature (IN)	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}
The Input of Renewable Resources from Economic Systems (FR)	6.41×10^{15}	3.11×10^{16}	5.75×10^{16}
The Input of Non-renewable Resources from Economic Systems (FN)	1.31×10^{14}	1.54×10^{16}	1.28×10^{17}
Wastes Internally Reused (R)	8.91×10^{15}	1.61×10^{16}	6.38×10^{16}
Total Yield (Y)	2.48×10^{16}	1.20×10^{17}	6.30×10^{17}

The proportion of the emergy from renewable resources to the total inputs in the system and the proportion of emergy from wastes reused to the total outputs reflect the level of renewable resources utilization and waste utilization of MFS, respectively. Thus, they are the basis for assessing the ecological benefits of the agricultural production system. As the calculation results show, the proportions of the emergy from renewable resources to the total inputs of the Ming-Qing pattern, the traditional pattern, and the new pattern of MFS were 99%, 68%, and 40%, respectively, and the proportions of the emergy from wastes reused to the total outputs were 53%, 33%, and 30%, respectively (Table 6). This indicates decreased utilization rate of renewable resources and wastes, and fewer ecological benefits in MFS with the development of patterns. Nonetheless, the new pattern, a combination of traditional agriculture and modern technology, is still in a process of enhancement, so its utilization rate of renewable resources and wastes will possibly increase as it matures.

Table 6. Emergy Proportion Relationship of Three Patterns.

Item	Calculation Formula	Ming-Qing Pattern	Traditional Pattern	New Pattern
the Proportions of the Emergy from Renewable Resources	(IR + FR)/I	99%	68%	40%
the Proportion of Emergy from Non-renewable Resources	(IN + FN)/I	1%	31%	60%
the Proportions of the Emergy from Wastes Reused	R/I	53%	33%	30%

Among all the emergy indices, the emergy investment ratio (EIR), environmental load ratio (ELR), emergy yield ratio (EYR), and emergy sustainability index (ESI) are selected as key indices to evaluate the sustainability level of MFS of the three patterns, which mainly concentrate on the production process. The calculation results are shown in Table 7. Among them, EIR reflects the carrying capacity of the natural environment for economic activities, EIR and ELR are used to evaluate the level of environmental load and the output efficiency of economic activities, respectively. According to these formulas, the lower the EIR and ELR are, the stronger capability MFS has to protect the natural environment; the higher the EYR is, the higher output efficiency of economic activities of MFS is. It can be found that, in terms of the capability for environmental protection, the MFS in the late Ming and early Qing dynasties performed the best while the new pattern performs the worst; as for the output efficiency, the Ming-Qing pattern also performed the best with the highest efficiency while the traditional pattern has the lowest one.

Table 7. Calculation Results of Emergy Indices of MFS.

Emergy Index	Calculation Formula	Ming-Qing Pattern	Traditional Pattern	New Pattern
Emergy Investment Ratio (EIR)	(FR + FN)/(IR + IN)	0.64	17.41	6.83
Environmental Load Ratio (ELR)	(IN + FN)/(IR + FR)	0.01	0.45	1.51
Emergy Yield Ratio (EYR)	Y/(FR + FN)	3.79	2.58	3.40
Emergy Sustainability Index (ESI)	EYR/ELR	479.64	5.67	2.26

ESI is an integrated index evaluating the sustainability level in the production process of MFS, representing the capability of protecting the natural environment and catering to the farmers' expectation for outputs altogether through agricultural production. As is displayed in Table 7, the MFS in the late Ming and early Qing Dynasties had the highest ESI at 479.64, as opposed to 2.26 of the new pattern. Therefore, the current sustainability level of MFS has significantly declined, compared to that in the Ming and Qing Dynasties. It is suggested that the new pattern of MFS needs to improve the sustainability level, advocating the urgency of preserving the GIAHS of Huzhou Mulberry-dyke and Fish-pond System.

5.2. Emergy Based Sustainability Evaluation about Mulberry-Dyke and Fish-Pond System

There are 5 first-level indicators and 21 second-level indicators in the sustainability evaluation index system. First, the values of second-level indicators were calculated and classified based on the emergy analysis. Then, the weights assigned to each second-level indicator shown in Table 8 were calculated according to the entropy method. It is noted that the emergy of natural resources (A1) per unit of land in the three patterns are similar, so the weight to A1 is relatively lower.

Table 8. Second-level Indicators and Weights.

First-Level Indicator	Second-Level Indicator	Ming-Qing Pattern	Traditional Pattern	New Pattern	Weight
Emergy of Renewable Resources (A)	Emergy of Natural Resources (A1)	1.14×10^{7}	1.14×10^{7}	1.14×10^{7}	2.99×10^{-8}
	Emergy of Seedling and Fry (A2)	1.12×10^{12}	2.34×10^{14}	3.53×10^{13}	5.61×10^{-2}
	Emergy of Labor (A3)	1.44×10^{13}	4.69×10^{12}	3.15×10^{12}	1.74×10^{-2}
	Emergy of Other Renewable Resources (A4)	3.96×10^{14}	0.00×10^{0}	0.00×10^{0}	9.00×10^{-2}
Emergy of Recycled Resources (B)	Emergy of Mulberry Leaves (B1)	4.77×10^{11}	6.01×10^{11}	1.49×10^{11}	1.03×10^{-2}
	Emergy of Silkworm Guano (B2)	4.18×10^{11}	5.95×10^{11}	1.18×10^{10}	3.00×10^{-2}
	Emergy of Pond Mud (B3)	7.48×10^{12}	1.28×10^{13}	5.12×10^{12}	5.78×10^{-3}
	Emergy of Other Recycled Resources (B4)	1.19×10^{13}	0.00×10^{0}	0.00×10^{0}	9.00×10^{-2}
Emergy of Non-renewable Resources (C)	Emergy of Fossil Energy (C1)	4.61×10^{11}	5.13×10^{12}	3.45×10^{12}	2.11×10^{-2}
	Emergy of Pesticides (C2)	0.00×10^{0}	5.90×10^{11}	4.26×10^{11}	3.43×10^{-2}
	Emergy of Fertilizers (C3)	0.00×10^{0}	8.45×10^{11}	1.86×10^{12}	3.92×10^{-2}
	Emergy of Synthetic Feeds (C4)	0.00×10^{0}	6.33×10^{13}	5.28×10^{13}	3.36×10^{-2}
	Emergy of Other Non-renewable Resources (C5)	0.00×10^{0}	1.92×10^{12}	2.80×10^{11}	5.87×10^{-2}
Emergy of Profits generated from Output (D)	Emergy of Profits from Silkworm and Mulberry Products (D1)	8.61×10^{13}	7.07×10^{12}	1.41×10^{13}	3.90×10^{-2}
	Emergy of Profits from Aquatic Products (D2)	1.17×10^{13}	6.06×10^{13}	6.49×10^{13}	1.42×10^{-2}
	Emergy of Profits from other Products (D3)	2.48×10^{13}	0.00×10^{0}	0.00×10^{0}	9.00×10^{-2}
Emergy of Costs in Input (E)	Emergy of Labor Costs (E1)	2.63×10^{13}	8.72×10^{12}	3.94×10^{12}	2.19×10^{-2}
	Emergy of Seedling and Fry Costs (E2)	4.59×10^{12}	2.22×10^{13}	5.81×10^{12}	2.08×10^{-2}
	Emergy of Feeds Costs (E3)	4.52×10^{12}	1.79×10^{13}	2.17×10^{13}	1.23×10^{-2}
	Emergy of Energy Costs (E4)	6.35×10^{12}	1.01×10^{12}	2.89×10^{12}	1.77×10^{-2}
	Emergy of Other Costs (E5)	9.63×10^{11}	3.46×10^{12}	2.71×10^{12}	9.00×10^{-3}

Eventually, the weighted summation of the indicators was performed, and the integrated sustainability evaluation indices of the three patterns (Table 9) were obtained. The integrated evaluation index in the production process can be acquired by summing up the emergy of the renewable resources, recycled resources and non-renewable resources and the integrated evaluation index in the circulation process equals the aggregation of the emergy embodied in the costs and profits. The total of the aforementioned two indices is the integrated sustainability evaluation index. Since the indicators have different directions of effects on the sustainability level of MFS, the index values can be positive or negative.

Table 9. Integrated Sustainability Evaluation Indices of MFS.

Evaluation Index	Ming-Qing Pattern	Traditional Pattern	New Pattern
Integrated Evaluation Index in the Production Process	43.14	18.10	−1.51
Integrated Evaluation Index in the Consumption Process	7.99	1.44	4.20
Integrated Sustainability Evaluation Index	51.13	19.54	2.69

With regards to the integrated evaluation index in the production process, the value of the MFS in the late Ming and early Qing Dynasties is the highest and the new pattern is the lowest, and even negative. Additionally, the renewable resources accounted for a large proportion of the total inputs in the Ming-Qing pattern while the non-renewable resources have replaced it in recent decades, resulting in the highest index value of the traditional pattern regarding the emergy of the non-renewable resources, followed by the new pattern. Overall, the index value of the emergy of the recycled resources and non-renewable resources has changed relatively slightly and the figures are also smaller, while that of the emergy of the renewable resources has experienced the largest fluctuation, so it becomes the major index influencing the change of the integrated evaluation index in the production process.

Furthermore, the descending order of the three patterns of MFS in the integrated evaluation index in the consumption process is the Ming-Qing pattern, the new pattern, and the traditional pattern. This index reveals the net profit of MFS. The higher the index is, the higher the net profit is, and the more willing the farmers will be to continuously employ the production pattern. Although the currency used in the late Ming and early

Qing Dynasties was different from nowadays, the conversion of values to emergy made it possible to compare the costs and profits in the two different periods. The results show that the MFS in the late Ming and early Qing Dynasties ranked the highest concerning the net profit of emergy per unit of land, followed by the new pattern and the traditional pattern, which appears to be consistent with the farmers' motivation for production.

The gap between the integrated sustainability evaluation index can comprehensively reflect the changes in the sustainability performance of the ecological-economic system of MFS. The higher index of the late Ming and early Qing Dynasties compared with those of the present patterns indicates that the sustainability level of this ecological agricultural model has decreased dramatically. By comparing the indices of the traditional and the new pattern, we found that although the integrated sustainability evaluation index of the traditional pattern is higher than the new pattern, the index in the consumption process of the new pattern has already surpassed the traditional one. The sustainability level will likely improve with the progress of the recycling mode in the new pattern.

6. Discussion

The MFS is regarded as a model of traditional ecological circular agriculture because of its material recycling and multi-level energy utilization in the agricultural production. The research result shows that the Ming-Qing pattern is the most sustainable; the comprehensive evaluation index of the production process, circulation process and sustainable development is far higher than the other patterns. This is because the external changes led to the separation, substitution and desertion of some original production steps of MFS, and further reduced the comprehensive utilization level of some resources in the system. This not only wastes resources, and affects environmental quality, but also limits the growth of income. The reduction of the comprehensive utilization level of the related resources is the fundamental reason for the decline of the sustainable development of MFS. This is similar to the development of MFS in the Pearl River Delta [42,43].

Regarding the question of whether we should try to restore it, the answer is no. Compared with the Ming-Qing pattern, the modern production technologies, labor input, and the pursuit of economic efficiency have undergone great changes. These changes have driven more farmers to abandon the traditional pattern of MFS and shrunk the production area. From the perspective of agricultural heritage system conservation, the Ming-Qing pattern is the essence of farmers' agricultural wisdom to adapt to the natural environment and social conditions. The traditional pattern is the legacy and display of this traditional agricultural wisdom in the contemporary era, which needs "dynamic conservation". Under the new economic and social conditions, we should excavate and inherit the traditional agricultural wisdom, and actively integrate new science and technology to explore a variety of modern patterns of MFS. The new pattern is a potential one, but many deficiencies still exist, and this needs to be improved further.

However, there are also some issues worthy of further discussion due to the existing limitations: Since Odum H. T. proposed the emergy theory and corresponding research methods in the 1980s, the emergy accounting method has been widely applied in a global range. By searching on Elsevier "Science Direct", we found that more than 1000 papers related to emergy had been published, indicating that this method has been rewarded by substantial scholars and researchers. Nevertheless, the unified measurement of UEVs is challenged by the lack of data, temporal, and spatial differences, etc. For instance, the UEVs of the silkworm guano and silkworm carbon cannot be traced back. (This research generated the data through projection.) This may lead to inaccurate accounting results.

This research focuses on the ecological-economic view in analyzing the sustainability development of Mulberry-dyke and Fish-pond System by the South Bank of Taihu Lake. However, its essential role in society, cultures and spirits, and its value in cultural inheritance and building of harmonious society are also vital to support for the sustainability development of MFS as a Globally Important Agricultural Heritage System site [44]. Limited by the research methodology employed, the contents of spirits and cultures are not included in the evaluation system and the sustainability performance of the present Mulberry-dyke and Fish-pond System is possibly undervalued.

7. Conclusions

Mulberry-dyke and fish-pond systems, a traditional eco-agricultural model in China, is most widely distributed, best preserved, and most large-scale by the South Bank of Taihu Lake. The "Zhejiang Huzhou Mulberry-dyke and Fish-pond System" was recognized as a site of GIAHS by FAO. It is in urgent need of dynamic conservation and adaptive management. Aiming at providing support for the conservation and management, this research first constructed an index system of sustainability evaluation about MFS based on the emergy accounting method, and then evaluated and analyzed the three patterns of MFS over different periods in this area. Here we draw the main conclusions:

In terms of evaluation methods, the comprehensive evaluation index of the MFS production process in different periods is consistent with the evaluation results of ESI. This verifies that the sustainability evaluation index in emergy analysis mainly focuses on the production process, ignoring the influence of the consumption process on the sustainability of MFS. The new sustainability evaluation index system of MFS that we constructed overcomes the deficiency of the emergy analysis in the evaluation.

In the new sustainability evaluation index system of MFS, the integrated evaluation index of the production process mainly reflects the ecological sustainability of the system, and the integrated assessment index of the consumption process mostly reflects the economic sustainability. This implies that the current MFS is less ecologically sustainable than the Ming-Qing pattern, and the new pattern performs better on the economic sustainability than the traditional pattern.

The descending order of the intertemporal patterns in the integrated evaluation index in the consumption process and the integrated sustainability evaluation index are the same: the Ming-Qing pattern, the new pattern, and the traditional pattern. This reflects that the new pattern adheres to the concept of the ecological cycle and integrates the modern agricultural technology. In accordance with the principle of "dynamic conservation" of MFS, a new pattern should be developed, and the sustainability of the system, especially the ecological sustainability, should be improved through further study.

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