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Analyzing the policy-driven adaptation of Important Agriculture Heritage Systems to modernization from the resilience perspective: a case study of Qingtian Rice-Fish Culture System, China

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Formulating effective conservation and management policies plays a key role in helping Important Agricultural Heritage Systems (IAHS) cope with the threats and challenges brought by modernization. An important criterion to measure their effectiveness is whether they maintain or enhance the resilience of IAHS. In this study, we first integrate IAHS resilience into the social-ecological systems (SES) framework and propose a SES-based analytical framework for IAHS resilience, which helps analyze how IAHS adapt to external disturbances under the drivers of policies. Then, we suggest the trade-off of ecosystem services as the surrogate of IAHS resilience and use the carbon footprint per unit output value as an indicator to quantify IAHS resilience. The application in Qingtian Rice-Fish Culture System (QRFCS) reveals that the rice-fish culture systems in three villages have formed different development models driven by different conservation and management policies when challenged by modernization, and have displayed different resilience in different development models. The development model centering on enlarged-scale fish farming in Xinpeng Village has shown the highest resilience; the development model with a combination of moderate-scale land management and experiential heritage tourism in Longxian Village has displayed a moderate resilience; and the development model with organic rice-fish culture integrated into terrace sightseeing tourism in Xiaozhoushan Village has shown the lowest resilience. Based on this, we put forward suggestions for maintaining and enhancing the resilience of QRFCS, so as to improve the management of the heritage system. We present that the results will not only enrich the resilience study of SES, but also promote IAHS management and regional sustainable development.

KEYWORDS

resilience, adaptation, modernization, social-ecological systems, carbon footprint, Important Agricultural Heritage Systems

1 Introduction

Holling (1973) first applied the concept of resilience to ecology by using the resilience and stability of ecosystems to explain the non-linear characteristics of ecosystem changes. Then the traditional perspective of resilience was extended from the succession of ecological communities to the evolution of social-ecological systems (SES) and the adaptive cycle theory was proposed to explain SES evolution (Holling and Gunderson, 2002). The concept of resilience was therefore revised to evolutionary resilience that involves the changes, adaptations, and transformations of a system in response to interferences (Quinlan et al., 2016). Instead of pursuing a steady state, the resilience of SES focuses on the dynamic adaptation processes to disturbances, which provides a useful framework to identify appropriate policy responses in regional management (Nelson et al., 2007). Based on the resilience assessment, managers can make more scientific decisions for regional management, and these decisions will affect SES resilience through specific regional management measures (Li et al., 2020). The resilience study of SES has been used to guide multiple aspects of regional management practices in response to sudden natural disasters (Ahern, 2011; Bellinson and Chu, 2019) or cumulative disturbances (e.g., biodiversity loss and global warming) (Hamin et al., 2018; Bellinson and Chu, 2019; Pilpola et al., 2019).

Initiated by FAO in 2002, Globally Important Agricultural Heritage Systems (GIAHS) are defined as remarkable farming systems and landscapes rich in globally significant biological diversity, which have evolved from the co-adaptation of a rural community with its environment and its needs and aspirations for sustainable development (FAO, 2018). It aims to establish a protection system for GIAHS and its landscape, biodiversity, knowledge and culture, and be recognized and protected worldwide, making it the basis of sustainable management (Koohafkan and delaCruz, 2011; Min et al., 2016). As of December 2023, the number of GIAHS designations in the world reached 86, distributed in 26 countries; among them, 22 GIAHS are located in China. At the national level, China, South Korea and Japan successively carried out the exploration and conservation of Nationally Important Agricultural Heritage Systems (NIAHS). The total number of China-NIAHS came to 188 by the end of 2023, distributed in 31 provinces, municipalities and autonomous regions in the mainland of China. GIAHS and NIAHS, collectively referred to Important Agricultural Heritage Systems (IAHS), are complex adaptive systems and typical representatives of SES. As outcomes of evolving from the co-adaptation of communities with their environment, IAHS still have stable productivity nowadays (Xie et al., 2011; Hu et al., 2016; Zhang et al., 2017a) and play an important role in maintaining such ecosystem services as biodiversity conservation (He et al., 2011; Park and Oh, 2017; Santoro et al., 2020), water and soil conservation (Li et al., 2016, Sun et al., 2016), greenhouse gas (GHG) emission reduction (Yuan et al., 2008; Wang et al., 2016; Cui et al., 2020), and environmental pollution reduction (Xu et al., 2010; Hu et al., 2013; Zhang et al., 2014). IAHS are therefore regarded as SES with high resilience that comes from their internally-regulated mechanisms to form feedback and synergism that reinforce the adaptation ability of them to disturbances (Sun et al., 2013; Zhang et al., 2017b; Ren et al., 2018).

However, after enduring the depredations of droughts, famines, plagues, floods and wars for centuries, IAHS are now facing threats and challenges brought by modernization (Jiao et al., 2016). Modernization is reflected in various aspects such as population dynamics, economic activities, and urbanization while the shocks it has brought on IAHS mainly include massive labor outflow, farmland abandonment, and influx of modern technologies (Jiao et al., 2021). In the context of modernization, many farmers in the heritage sites, especially young farmers, give up traditional agricultural production and go to towns and cities as migrant workers (Qiu et al., 2016; Su et al., 2020b). Influenced by a massive labor outflow, the phenomenon of farmland abandonment has occurred to different degrees in the heritage sites. A survey conducted by Jiao et al. (2016) found that the proportion of migrant workers reached 65% while the proportion of abandoned farmland reached 33% in the core area of Qingtian Rice-Fish Culture System, China in 2014. Park and Oh (2017) estimated that approximately 26% of terraced fields had been abandoned in Traditional Gudeuljang Irrigated Rice Terraces in Cheongsando, South Korea, due to aging population and decreasing number of farmers. Besides, the reduction of farmland area in the heritage sites has been profoundly affected by urbanization. Zhang et al. (2016) pointed out that the land encroachment by urban construction was one of the main reasons for the sharp decline in jasmine planting area in Jasmine and Tea Culture System of Fuzhou City, China. Bai et al. (2014) mentioned that housing and road construction had led to a decrease in the area of stacked fields in Xinghua *Duotian* (stacked fields) Agrosystem, China. Further, driven by economic development, the influx of modern technologies has significantly changed traditional agricultural production modes in many heritage sites. Nahuelhual et al. (2014) found that the protection of local potato varieties had been seriously threatened as more and more commercial potato varieties were introduced into Chiloé Agriculture, Chile. Yang et al. (2017) mentioned that the replacement of rice by dry crops had not only threatened the local rice culture but also threatened the terraced landscape in Hani Rice terraces of China. Bai et al. (2014) pointed out that with the increased usage of chemical fertilizers, natural fertilizers widely used in the past were rarely used anymore in Xinghua *Duotian* Agrosystem, China.

When a SES is disturbed by external factors, its internal subsystems and the coupling relationship between them will change, and resist or adapt to the disturbance; if the intensity of disturbance exceeds a certain range, the SES may undergo a sudden positive or negative change that is often irreversible (Garmestani, 2014). Therefore, when the disturbances faced by IAHS far exceed their capacity to offset such problems via self-organization, policies must be taken to mitigate or adapt to disturbances and protect IAHS from undesirable transformations that often result in unexpected social and/or ecological consequences. For this reason, many heritage sites have formulated necessary policies to help IAHS respond to the threats and challenges induced by modernization, such as establishing eco-compensation mechanisms (Yiu, 2014; Liu et al., 2018) promoting eco-labelling products (Satoshi et al., 2014; Kajima et al., 2017), and developing sustainable tourism (Yang et al., 2018; Su et al., 2020a). Then it has become a general concern whether these policies are effective. An important criterion to evaluate the effectiveness is whether these policies maintain or enhance the resilience of IAHS to avoid them falling into an undesirable cycle. When challenged by modernization, the resilience of IAHS is not only important for themselves to maintain a desirable state and ecosystem services, but also serves as a key foundation for sustainable development of heritage sites. Therefore, revealing the policy-driven adaptation process and

FIGURE 1
Qingtian Rice-Fish Culture System, China. Source: Bureau of Agriculture and Rural Affairs, Qingtian County, Zhejiang Province, China.

assessing the resilience of IAHS can not only answer the effectiveness question concerning management policies, but also help managers understand the policy responses in IAHS management, thus promoting them to make more efficient decisions.

The aim of this study is to establish a methodology to reveal the policy-driven adaptation process of IAHS and assess the policy effectiveness by the changes of IAHS resilience. To testify the methodology, we choose Qingtian Rice-Fish Culture System (QRFCS) as the case study, which is the first GIAHS in China and also a China-NIAHS. Firstly, we integrate IAHS resilience into the SES framework and propose a SES-based analytical framework for IAHS resilience, which helps analyze how IAHS mitigate or adapt to external disturbances through self-regulation. Then, we introduce the carbon footprint (CF) method to characterize IAHS resilience and use the ratio of CF to output value to quantitatively assess IAHS resilience. Next, we apply the methodology to QRFCS. Taking three typical villages as examples, we analyze how the rice-fish culture systems in Qingtian County have formed different development models driven by different management policies when challenged by modernization, and what are the differences in their resilience in different development models. Finally, we discuss the effectiveness of different management policies and put forward suggestions for maintaining and enhancing the resilience of QRFCS, so as to improve the management of the heritage system. The contribution of this study is to enrich the resilience study of SES on the one hand and to promote IAHS management and regional sustainable development on the other hand.

2 Methodology

2.1 Study area

Qingtian County is located in the southeastern part of Zhejiang Province, China. The Ou River runs through the whole territory from northwest to southeast. The total area of the county is 2,493 km^2, of which 90% is covered by mountains, 5% by water bodies and only 5% by farmland. Qingtian County has a subtropical monsoon climate, with an average annual sunshine time of 1,664 h, an average annual precipitation of 1,698 mm, and an average annual temperature of 18.6°C. Qingtian County is rich in forest resources, with a forest cover rate of 81.63%, and dominated by evergreen broad-leaved forest, coniferous and broad-leaved mixed forest and moso bamboo forest. The topography and moist climate conditions have long rendered this area suitable for wet rice production in the small man-made terraces on the upland valley sides. A traditional economy of rice and fish has been developed in the terraces over 1,300 years and is ingeniously supported by a gravity-flow irrigation system (Figure 1). The rice-fish culture makes full use of the symbiotic relationship between rice and fish, and realizes the trinity of economic, social and ecological benefits. The QRFCS was recognized by FAO as one of the first GIAHS in 2005. The Ministry of Agriculture and Rural Affairs (MARA) listed it as one of the first batch of China-NIAHS in 2013. Fangshan Town in the southeast of Qingtian County is defined as the core area of the heritage system, while Renzhuang Town, Xiaozhoushan Town and other towns with rice-fish culture are defined as the peripheral area.

The registered population of Qingtian County was about 572,300 in 2020, the gross domestic product (GDP) was 24.913 billion *yuan*, and the *per capita* disposable income was 38,531 *yuan*. Qingtian County is renowned as the hometown of overseas Chinese people, with a total of 330,000 overseas Chinese distributed in 121 countries and regions in the world. Since the onset of the Qing Dynasty, the rural people of the county have opted for domestic and overseas migration as one way to relieve the pressures and constraints of poverty. With the continuous development of economy and under the influence of modernization and urbanization, the scale of overseas immigrants has increased rapidly, and the number of migrant workers inside and outside Zhejiang Province has also increased greatly. Under such a social and economic background, the young labor force in Qingtian County has sharply reduced, and the land abandonment phenomenon is increasingly serious, which has badly affected the sustainable development of QRFCS. To cope with the impact of modernization and promote the conservation of the heritage system, Qingtian County has established an agricultural heritage conservation fund that provides 3 million *yuan* annually to subsidize farmers to continue rice-fish culture, especially in Fangshan Town of the core area. At the same time, other towns in the peripheral area have explored different development models of rice-fish culture. For example, Renzhuang Town has introduced modern technologies to enlarge the scale of fish farming and increase the economic output of rice-fish culture; Xiaozhoushan Town has made use of the terraced landscape to promote the integrated development of rice-fish culture and tourism.

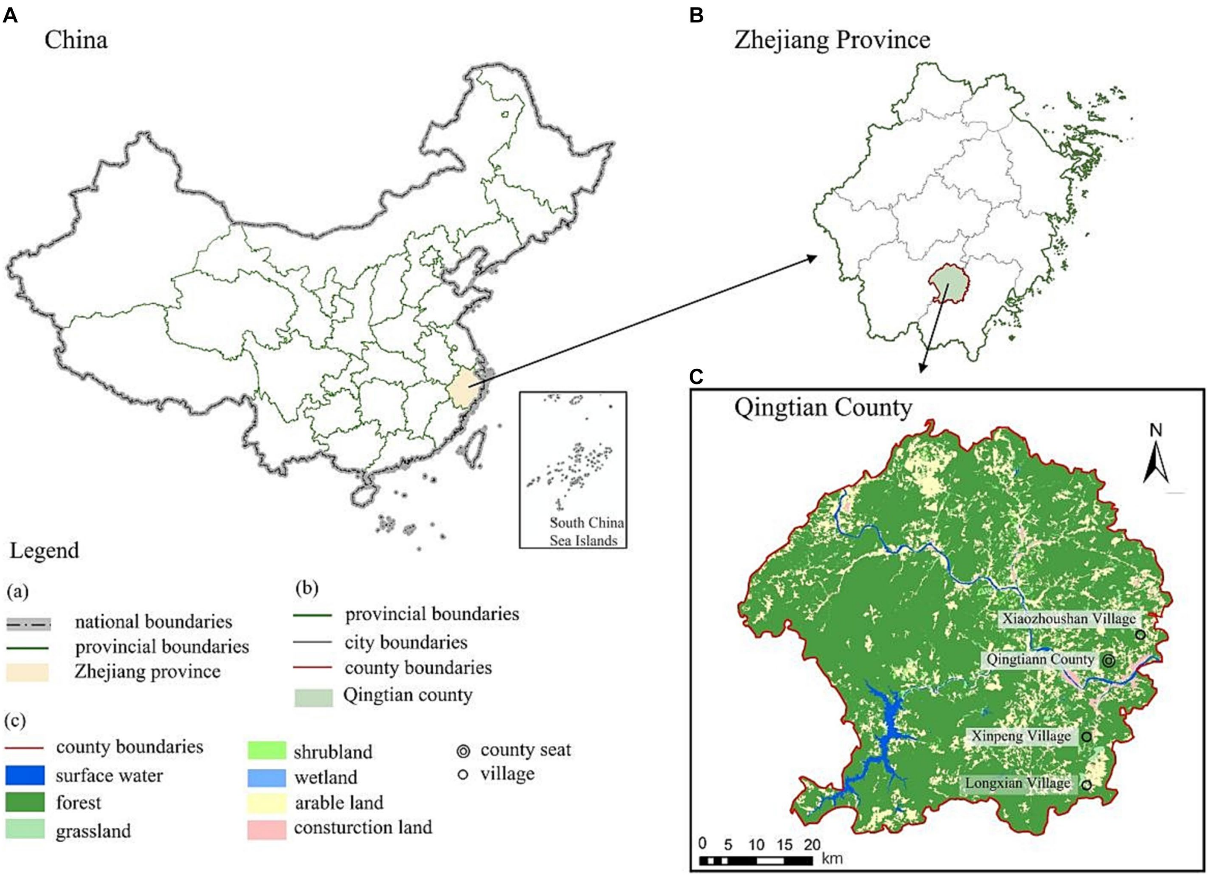

FIGURE 2
Location of the study area.

We choose Longxian Village in Fangshan Town, Xinpeng Village in Renzhuang Town and Xiaozhoushan Village in Xiaozhoushan Town as the study area (Figure 2). The three villages are subjected to similar threats and challenges brought by modernization, but have adopted different conservation and development policies and their rice-fish culture systems have formed different development models. In other words, driven by different policies, the rice-fish culture systems have reached different but desirable states through self-regulation and their resilience has also changed in the adaptation process.

2.2 SES-based analytical framework

The SES framework, proposed by Ostrom (2009), is a multi-scale, trans-temporal analytical framework that solves multi-dimensional coupling interaction problems (McGinnis and Ostrom, 2014). The core idea of the SES framework is that the actors (A) utilize, maintain, or consume resource units (RU) from the changing resource systems (RS) that are constrained by a set of rules (GS); the resource conditions and governing rules constitute specific action situations (AS) and influence the interactions (I) and outcomes (O) that take place in them; and, at the same time all of these are influenced by the social, economic and political settings (S) and the related ecosystems (ECO) (Ostrom, 2009). The SES framework provides a comprehensive approach to analyze the interaction mechanisms between human and nature, and has been widely applied to guide regional environmental management and to solve sustainable governance problems, such as the management of agriculture, forestry and fishery production (Auclair et al., 2011; Hunt et al., 2013; Moritz et al., 2016), the prevention and mitigation of natural disasters (Martin and Schlüter, 2015; Brunner and Grêt-Regamey, 2016), and the governance of ecological cities (Wen et al., 2015; Bellinson and Chu, 2019).

IAHS, as complex adaptive systems, are composed of ecological and social subsystems that are inter-dependent in various ways and affect each other to some degree (Fuller and Min, 2013). Besides interacting with each other, the subsystems are also influenced by external forces, and the influences are ultimately manifested as changes in the structure, function and state of IAHS. When faced with internal or external interference or disturbance, IAHS will finally reach a new equilibrium state through the self-regulation of each subsystem, which is called adaptation (Fuller et al., 2015). Therefore, the resilience of IAHS has been formed through the continual adaptation of human beings and their livelihood activities to the potentials and constraints of the environment and their shaping of the landscape and the biological environment to different degrees.

Since it can organize and track numerous variables and possible explanations involved, the SES framework will help better analyze the complex interactions between IAHS subsystems and clarify the dynamic mechanisms of IAHS resilience. Therefore we establish the SES-based analytical framework for IAHS resilience and redefine the variables in this framework (Figure 3).

We apply the SES-based analytical framework for IAHS resilience to QRFCS and analyze how the rice-fish culture systems have formed different development models driven by different policies and how their resilience have changed in the formation process of different development models. Before the framework is employed, we firstly identify and describe the variables involved in the QRFCS. ECO and S have been already described in the study area, and other variables are described as follows:

- Resource systems (RS) mainly involve subsystems of biological resources, land use, production inputs, and buildings.
- Resource units (RU) include rice, fish (paddy carp) and rapeseed in the biological resource subsystem, farmland (mainly rice terraces) in the land use subsystem, fertilizers, pesticides, feed and fuel in the production input subsystem, and houses and roads in the building subsystem.
- Actors (A) include both farmers engaged in the rice-fish culture and other stakeholders such as governments, enterprises, and research institutes.
- Governance systems (GS) involve subsystems of knowledge, culture, organization and policy. Specifically, the knowledge subsystem includes both traditional production knowledge of local farmers and modern technologies introduced by research institutes. The cultural subsystem involves festival customs and food culture formed by local farmers. The organizational subsystem mainly involves farmer specialized cooperatives. The policy subsystem includes conservation planning, supportive policies and subsidies formulated by local governments.
- Interactions (I) refer to the processes in which variables of rice-fish culture systems interact with each other to form different development models.
- Outcomes (O) are the changing results of resilience of rice-fish culture systems in different development models.

2.3 CF-based evaluation method

Trade-offs occur when multiple ecosystem services are competitively used (Rodríguez et al., 2006), that is, providing or enhancing one service is at the expense of losing or restricting another

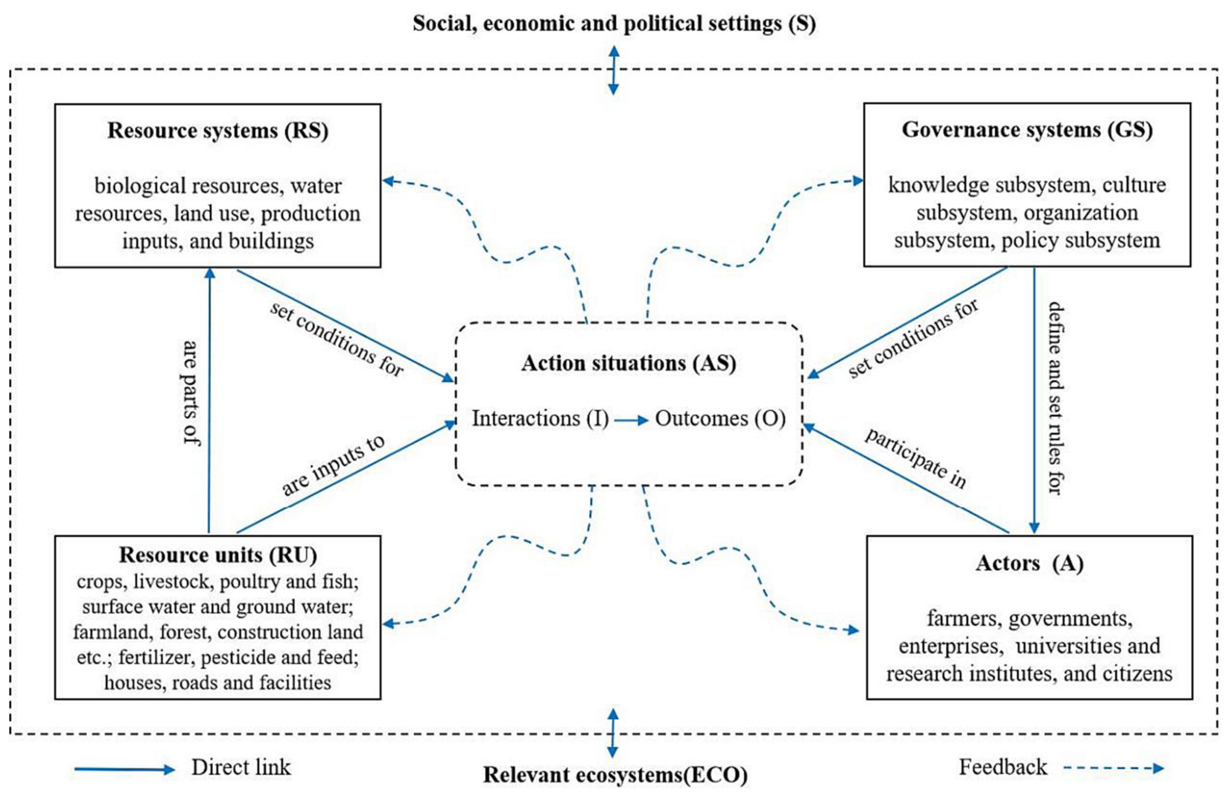

FIGURE 3
The SES-based analytical framework for IAHS resilience. The figure is drawn with reference to McGinnis and Ostrom (2014). S refers to the social, economic and political background of the IAHS site, such as socio-economic development level, political stability, etc. ECO refers to the ecological and environmental conditions of the IAHS site, such as climate type, landform, soil types, hydrological conditions, etc. RS refers to the physical system utilized, managed and maintained by actors, composed of subsystems of biological resources, water resources, land use, production inputs, buildings, etc. RU refers to specific components of the resource system. A refers to those involved in the utilization and management of resources, which are also the stakeholders in the conservation of IAHS. GS refers to the rule system according to which actors utilize and manage resources, composed of subsystems of knowledge, culture, organization, policy, etc. I refers to the interacting processes between variables, which are also the changing processes of IAHS resilience. O refers to the results of the interactions between variables and also the changing results of IAHS resilience.

(Bennett et al., 2009). Trade-offs particularly exist between provisioning and regulating services (Lin et al., 2018; Stosch et al., 2019) and the most common trade-off is found between food production and other services (Zheng et al., 2019; Aryal et al., 2022). To realize more efficient management, managers must coordinate the trade-off relationships among ecosystem services to achieve win-win outcomes (Howe et al., 2014; Wong et al., 2015). When it comes to SES management, a win-win outcome often represents a desirable state of the system with a low level of trade-offs among ecosystem services, and the resilience actually focuses on the ability of the system to achieve such a desirable state after being disturbed. From this perspective, we think the trade-off relationship among ecosystem services can be used as the surrogate of the SES resilience. For a SES that has reached a desirable state after being disturbed, a higher resilience means there is a lower level of trade-offs among ecosystem services in it.

IAHS are not only typical SES, but also complex agroecosystems that aggregate agricultural production and related human social and economic activities at different scales. Studies have found that complex agroecosystems that rely on spatial, temporal, and/or biological diversity to support self-regulating feedback and synergism can lend resilience to adverse conditions while maintaining productivity and ecosystem service provision (Di Falco and Chavas, 2008; Khumairoh et al., 2012; Gaudin et al., 2013). The high resilience of complex agroecosystems is characterized by the stable productivity in the short term, but in the long term it refers to the ability to reliably produce enough food, fuel, and fiber without detrimental effects on the maintenance of other ecosystem services (Peterson et al., 2018). Therefore, we believe that the trade-off relationship between the food production service and one or some of other ecosystem services can be used as indicators to quantitatively assess the resilience of IAHS. When it comes to the QRFCS, the food production service refers to the capacity of the system for producing rice and fish. Limited by the available data, in this study we mainly consider the GHG emission reduction service among other ecosystem services that the QRFCS maintains and take the CF per unit output value born from the CF method to measure the trade-off between the two services.

CF is expressed in CO_2 emission equivalent and refers to the total amount of direct and indirect GHG emissions caused by an activity or accumulated in the life cycle of a product (Wiedmann and Minx, 2008; Dubey and Lal, 2009). As an effective tool for environmental impact assessment of GHG emissions, the CF method has been widely used to evaluate the impact that GHG emissions from agricultural production have imposed on the environment (Finkbeiner, 2009; Huang et al., 2016; Clavreul et al., 2017; Diksha and Devakumar, 2018). In this study, we use the CF per unit output value as an indicator to assess the resilience of the QRFCS. The output value reflects the productivity of the QRFCS, that is, its capacity for producing rice and fish; the CF reflects the environmental impact of the QRFCS in terms of GHG emissions, and also its capacity for reducing GHG emissions. A larger CF per unit output value means a lower resilience of the QRFCS that is brought by a higher level of trade-off between the food production service and the GHG emission reduction service, while a smaller CF per unit output value represents a higher resilience resulting from a lower level of trade-off between them. Specific calculation processes are shown in Appendix I.

Other economic activities that may have GHG emissions, like tourism, are not considered in current CF accounting, as the rice-fish culture is the most important part of QRFCS. Different policies adopted by different villages share a common purpose that is to help the rice-fish culture survive from the disturbances from modernization. Therefore, when measuring the resilience of QRFCS, we care more about whether the rice-fish culture is well maintained, still having productivity and providing such important ecosystem services as GHG emission reduction. Besides, we assume that the resilience of the rice-fish culture system in different villages is similar before different policies are implemented. Thus, we only compare the CF per unit output value among different villages after implementing different policies, without analyzing the dynamic changes of the CF per unit output value of a specific village before and after a specific policy is implemented.

2.4 Data collection

Data for this study were collected in July 2019 and August 2020, in Longxian Village, Xinpeng Village and Xiaozhoushan Village of Qingtian County, by means of questionnaire surveys and interviews. The questionnaire data are mainly used in the CF-based evaluation of the resilience of the rice-fish culture systems in different villages. The interview data are mainly used in the SES-based analysis of the policy-driven adaptation of the rice-fish culture systems in different villages.

The survey questionnaire took the growth period of rice and fish from March to October 2018 as the time boundary, and involved information mainly on the agricultural production mode (i.e., rice monoculture, rice-fish culture), the area of rice planting, the scale of fish farming, the inputs of agricultural production, and the yield and output value of rice and fish. With the stratified random sampling, a total of 35 households were investigated in Longxian Village, among which 33 households were engaged in rice-fish culture. The investigated area of rice planting was 13.5 ha, of which the area of rice-fish culture was 11.2 ha. A total of 23 households were investigated in Xinpeng Village, among which 21 households were engaged in rice-fish culture. The investigated area of rice planting was 8.13 ha, of which the area of rice-fish culture was 6.23 ha. A total of 21 households were investigated in Xiaozhoushan Village, among which 19 households were engaged in rice-fish culture. The investigated area of rice planting was 22.13 ha, of which the area of rice-fish culture was 22.07 ha. The survey covered most of the households engaged in rice-fish culture in the study area. The investigated households accounted for more than 85% of the local households engaged in agricultural production, and the investigated rice planting area accounted for more than 70% of the total rice planting area in the study area. Since male laborers in households were mainly engaged in the rice-fish culture, about 90% of the subjects were male (Table 1). The majority of the subjects were over 50 years old and some of them were over 70 years old.

The core stakeholders of the QRFCS include farmers, governments, enterprises, and research institutes. Therefore, we conducted semi-structured interviews that cover all the core stakeholders. With a pre-conceived guide, three standard questions were asked in each separate interview while additional questions were developed depending on the interviewing process. The standard questions were (i) what threats and challenges were facing the rice-fish culture system; (ii) what polices and in what ways were implemented for the rice-fish culture system; and (iii) whether and how the rice-fish culture system benefited from the implementation of the policies.

TABLE 1 Information of the subjects in the questionnaire surveys.

Village	Total number	Gender		Age				
		Male	Female	≤50	50 < Age ≤ 60	60 < Age ≤ 70	70 < Age ≤ 80	>80
Longxian	35	31	4	3	12	15	4	1
Xinpeng	23	23	0	0	6	15	2	0
Xiaozhoushan	21	17	4	0	3	10	8	0

TABLE 2 GHG emission factors of various agricultural production inputs.

Item		GHG emission factor	Data source
Chemical fertilizer	Nitrogen fertilizer	1.53 $kgCO_2$-eq/kg	Liu et al. (2010)
	Compound fertilizer	1.77 $kgCO_2$-eq/kg	Liu et al. (2010)
Pesticide		16.61 $kgCO_2$-eq/kg	Ecoinvent Database (2011)
Feed	Wheat	1.01 $kgCO_2$-eq/kg	Wang (2018)
	Corn	0.79 $kgCO_2$-eq/kg	Wang (2018)
	Rapeseed	1.33 $kgCO_2$-eq/kg	Chen et al. (2019)
	Commercial feed	0.10 $kgCO_2$-eq/kg	Cui et al. (2022)
Fuel	Gaoline	3.12 $kgCO_2$-eq/kg	Lal (2004)

Group interviews were conducted with government officials, as this form of interview was more efficient and feasible for different government sectors to co-produce knowledge. By contrast, in-depth individual interviews were conducted with farmers, entrepreneurs and researchers because they can be free to express their authentic attitudes. We organized two group interviews for the agricultural bureau and the governments of the three towns, and a total of eight government officials were interviewed. We conducted eleven in-depth interviews with seven local farmers, two entrepreneurs and two researchers.

Besides, we collected some statistical data on the population and land of the three villages in the past five years from the governments of the three towns. The statistical data are mainly used for the in-depth description of the S and ECO of different villages. We also extracted GHG emission factors of various types of agricultural production inputs from the China Life Cycle Database 0.7 (Liu et al., 2010), the Ecoinvent Database 2.2 and relevant studies (Table 2), for the CF-based evaluation of the resilience of the rice-fish culture systems.

3 Results

3.1 Adaptation processes driven by different policies

3.1.1 Longxian Village

Longxian Village is located in the core area of the heritage system. However, as more farmers migrate to cities or even overseas, the permanent population of the village is now less than one third of the registered population. Since 2015, only about 40 households in the village have been still farming, and the actual number of farmers has decreased to less than 60. Due to the massive outflow of labors, the problem of land abandonment in Longxian Village is very serious. As estimated, the proportion of paddy field abandonment was as high as 34% in 2015. At the same time, the village is also faced with the problem of egrets preying on fish, which has greatly reduced the output of fish and the enthusiasm of farmers to continue rice-fish culture. In order to minimize economic losses, farmers have to reduce the feed input, which further aggravates the decline of fish output.

To promote the conservation and inheritance of QRFCS, Qingtian County government has formulated a planning for heritage conservation and implemented a series of supportive policies. In 2015, the county government began to provide planting subsidies for large-scale rice farmers all over the county, and in 2018, the government began to provide ecological subsidies for farmers who continued rice-fish culture in Longxian Village. With the support of these policies, many farmers in Longxian Village enlarged the land management scale through land transfer and land reclamation. The total area of rice-fish culture in the village increased from 11.6 ha in 2015 to 15.5 ha in 2018, and the proportion of paddy field abandonment has decreased from 34 to 26%. At the same time, the county and town governments strengthened infrastructure construction in Longxian Village to develop sustainable tourism and to promote its integration with heritage conservation. Guided by the governments, some farmers began to run farmhouse restaurants and homestays, providing local delicacies for tourists, while others began to build small museums out of idle houses. These measures of tourism development have not only benefited some farmers, but also contributed to the maintenance of the rice-fish culture in the village.

In the adaptation process of Longxian Village to modernization, farmers (A1), governments (A2) and research institutes (A3) are the main actors, among which the governments are the most powerful ones. Supported by research institutes, the governments formulated a heritage conservation planning, based on which a series of subsidy policies (GS3) were implemented. The conservation planning and subsidy policies have changed the governance system that was originally dominated by traditional production knowledge (GS1), food culture and festival customs (GS2), and then changed the production and management behavior of farmers. With the support of the subsidy policies, many farmers increased the area of rice-fish culture (RU1) through land transfer and land reclamation. The moderate-scale land management has enabled them to achieve a small increase in economic gains of rice and fish (RU2) with relatively low inputs (RU3). Some farmers utilized food culture and farmhouses (RU4) to develop small-scale, experiential heritage tourism, which has to some extent contributed to the maintenance of the rice-fish culture in the village. Through the interactions among subsystems, the rice-fish culture system in Longxian Village has reached a desirable state where the moderate-scale land management (AS1) is combined with the experiential heritage tourism (AS2) (Figure 4). This development model, mainly driven by the subsidy policies, has well maintained the traditional rice-fish culture system in the village.

3.1.2 Xinpeng Village

Xinpeng Village is located in Renzhuang Town in the peripheral area, with convenient transportation and a large area of flat rice fields. Similar to Longxian Village, Xinpeng Village is also confronted with such problems as aging population, outflow of young labors, and land abandonment. To respond to these challenges brought by modernization, Xinpeng Village chose to introduce modern technologies in cooperation with Zhejiang University, Shanghai Ocean University and other research institutes. Supported by the county and town governments, a rice-fish research and demonstration base was founded in Xinpeng Village, which integrated traditional knowledge and modern technologies to establish an efficient development model of rice-fish culture. Farmers in the village set up a specialized cooperative and accepted the training of research institutes. After mastering modern technologies, they successfully expanded the scale of fish farming and increased the fish output significantly. From the sales of fish products, Xinpeng farmers obtained considerable economic benefits.

Farmers (A1), governments (A2) and research institutes (A3) are the main actors in the adaptation process of Xinpeng Village to modernization, among which governments and research institutes have played a very important role. In addition to providing subsidies for large-scale rice farmers (GS2), governments cooperated with research institutes to introduce modern technologies (GS1-2) into the governance system of the rice-fish culture system. The combination of traditional production knowledge (GS1-1) and modern technologies has created a new action situation. With the policy guidance and technical support, farmers established a specialized cooperative (GS3), successfully expanded the scale of fish farming, realized the high output of fish (RU2), and increased the economic income of rice-fish culture. As the economic income has increased greatly, more farmers are willing to continue rice-fish culture and increase production inputs (RU3), and more abandoned farmland have been reclaimed and transferred (RU1). Through the interactions among subsystems, the rice-fish culture system in Xinpeng Village has reached a desirable state and formed a development model centering on the enlarged-scale fish farming (AS1), which has well realized the modernized development of rice-fish culture (Figure 5).

3.1.3 Xiaozhoushan Village

Xiaozhoushan Village is located in Xiaozhoushan Town in the peripheral area, where large-scale and magnificent terraced paddy fields are distributed. Due to the high altitude and inconvenient transportation, Xiaozhoushan Village faces more serious problems of labor loss and land abandonment than Longxian Village and Xinpeng Village. In such a situation, it chose to develop tourism in response to the challenges brought by modernization. Since 2012, Xiaozhoushan Village has been focusing on terraced landscape, into which characters and symbols are planted using rapeseed fields in spring and paddy

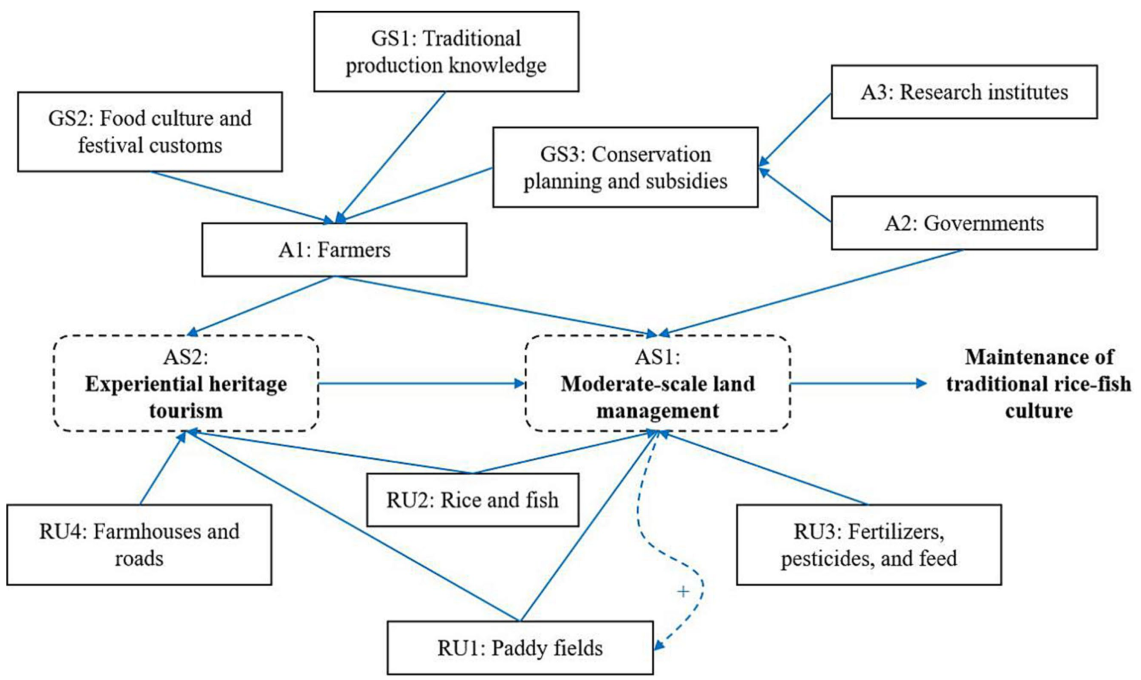

FIGURE 4
The interaction process of the rice-fish culture system in Longxian Village.

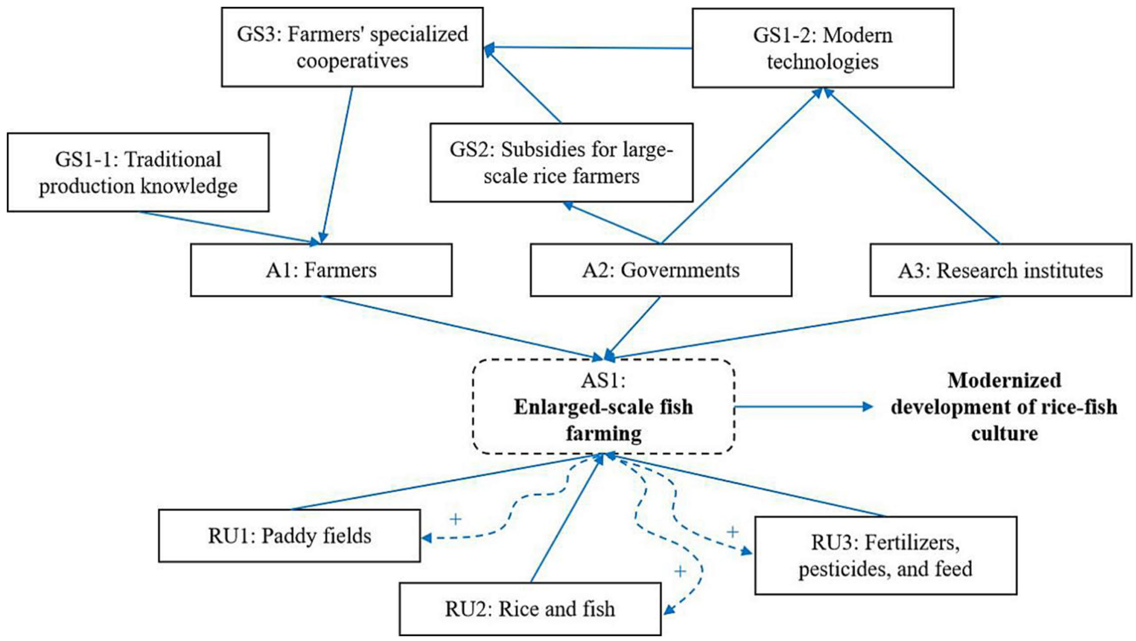

FIGURE 5
The interaction process of the rice-fish culture system in Xinpeng Village.

fields in autumn, attracting a large number of tourists and photography enthusiasts. On this basis, the county and town governments built hiking trails, viewing platforms and other infrastructure, carried out publicity and tourism activities with festival customs, and introduced a number of enterprises to operate specialty restaurants and hotels. In 2014, Xiaozhoushan Village received 80,000 tourists, with a tourism income of 1.6 million yuan; in 2019, the number of tourists increased to 180,000, and the tourism income increased to 4.8 million yuan. The key attraction of Xiaozhoushan Village to tourists lies in the sustainable use of terraced paddy fields. With the support of governments, farmers of the village set up a specialized cooperative to transfer and reclaim abandoned land, planted rapeseed on a large scale and performed organic rice-fish culture.

Farmers (A1), governments (A2) and enterprises (A3) are the main actors in the adaptation process of Xiaozhoushan Village to modernization, of which governments and enterprises play a leading role. Besides providing subsidies for large-scale rice and rapeseed farmers, the county and town governments supported local farmers to conduct organic rice-fish culture (GS3-1), and formulated supportive policies for tourism development (GS3-2). These supportive policies have changed the governance system that was originally dominated by traditional knowledge (GS1) and traditional culture (GS2). Influenced by these policies, farmers participated in agricultural production and tourism management in the form of the specialized cooperative (GS4), which formed a close dependent relationship between agriculture and tourism. The participation of enterprises pumped external funds into the tourism development on the one hand, and on the other hand, it provided diversified options for farmers to maintain their livelihood. Some farmers worked part-time or full-time in specialty restaurants and hotels (RU4), thus participating in tourism management and earning certain incomes. As the tourism income has been distributed to farmers directly (as wages) or indirectly (as subsidies), more farmers are willing to plant rapeseed extensively (RU2-2), and reduce chemical inputs (RU3) to conduct organic rice-fish culture (RU2-1), and more abandoned land have been reclaimed and transferred (RU1). Through the interactions among subsystems, the rice-fish culture system in Xiaozhoushan Village has reached a desirable state and formed a development model in which the organic rice-fish culture (AS2) is closely integrated into the terrace sightseeing tourism (AS1) (Figure 6).

3.2 Resilience assessment based on the CF method

The CFs of production inputs of rice-fish culture systems in different villages were calculated with formula (1) of Appendix I. From Table 3, we can see that the CF of production inputs in Xinpeng Village is higher than that in Longxian Village and Xiaozhoushan Village, and the CFs of pesticide, feed and gasoline inputs are significantly higher in Xinpeng Village than those in Longxian Village and Xiaozhoushan Village.

The CFs of production processes of rice-fish culture systems in different villages were calculated using formulas (2) to (6) of Appendix I. Due to the high input of nitrogen fertilizers, the CF of the production process in Longxian Village is higher than that in Xinpeng Village and Xiaozhoushan Village (Table 4).

The CFs of rice-fish culture systems in different villages were calculated with formula (7) of Appendix I. Due to the relatively small difference in CFs of production processes, CFs of production inputs have become the main reason for the difference in carbon footprints of rice-fish culture systems in different villages. The development model of Xinpeng Village focused on expanding the scale of fish farming, so the production inputs such as feed have increased

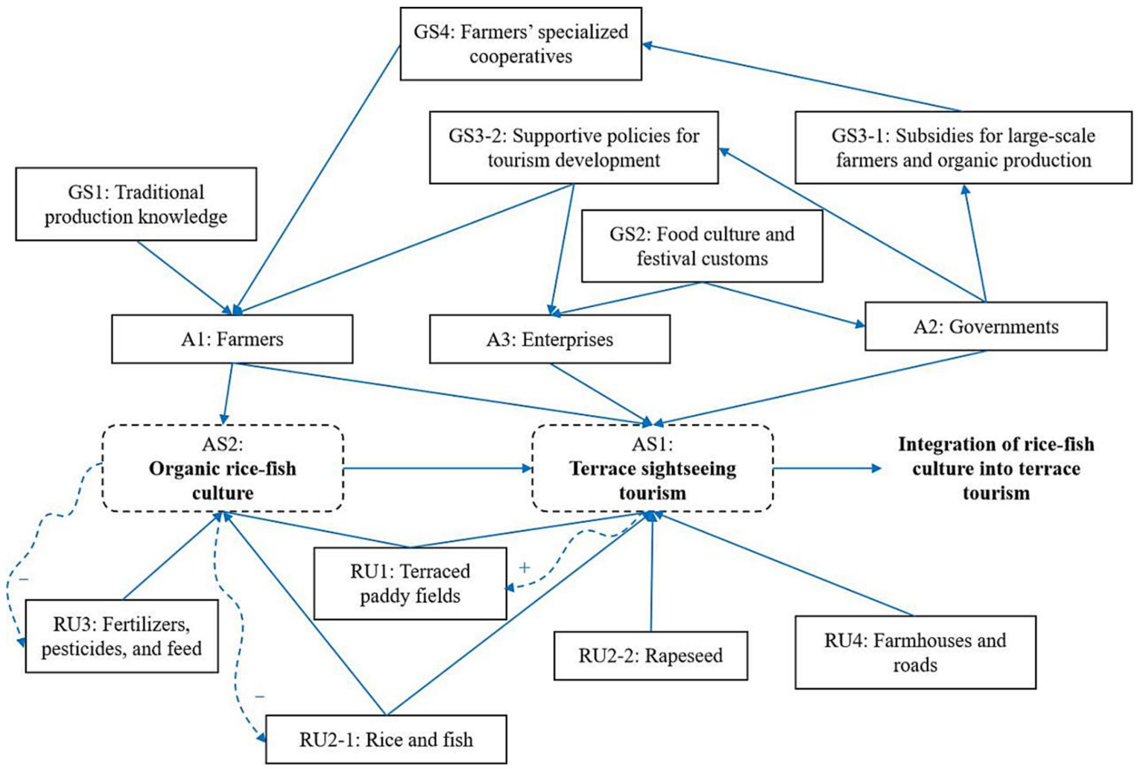

FIGURE 6
The interaction process of the rice-fish culture system in Xiaozhoushan Village.

TABLE 3 Carbon footprints (CFs) of production inputs of rice-fish culture systems in different villages (kgCO_2-eq/ha).

Village	Chemical fertilizer		Pesticide	Feed				Fuel	Total
	Nitrogen fertilizer	Compound fertilizer		Wheat	Corn	Rapeseed	Commercial feed	Gasoline	
Longxian	278.2	1116.2	43.2	222.6	265.5	0	0	133.2	2058.9
Xinpeng	175.2	1095.3	853.8	151.5	51.7	928.8	232.7	278.4	3767.4
Xiaozhoushan	39.3	629.4	198.3	280.1	0	381.6	0	166.7	1695.4

TABLE 4 CFs of production processes of rice-fish culture systems in different villages (kgCO_2-eq/ha).

Village	CF_{CH4}	CF_{N2O}			$CF_{process}$
		$CF_{N2Odirect}$	$CF_{N2Oindirect}$	Total	
Longxian	4306.5	705.6	161.8	867.4	5173.9
Xinpeng	4306.5	535.6	122.9	658.5	4965.0
Xiaozhoushan	4306.5	221.6	50.8	272.4	4578.9

significantly, which has made the CF of the rice-fish culture system in Xinpeng Village the highest (Table 5).

The CFs per unit output value of rice-fish culture systems in different villages were calculated using formula (8) of Appendix I. From Table 6, we can see that the fish output in Xinpeng Village is 3.9 times and 6.6 times that in Longxian Village and Xiaozhoushan Village. The high economic value of the fish has increased the total output value of the rice-fish culture system. Since Xinpeng Village has a significant advantage in the fish output, its output value per unit area is far higher than that of Longxian Village and Xiaozhoushan Village, 2.8 times and 4.3 times, respectively. Therefore, although the CF of the rice-fish culture system in Xinpeng Village is higher than that of Longxian Village and Xiaozhoushan Village, the CF per unit output value in Xinpeng Village is smaller than that of Longxian Village and

TABLE 5 CFs of rice-fish culture systems in different villages (kgCO_2-eq/ha).

Village	CF_{input}	$CF_{process}$	$CF_{agriculture}$
Longxian	2058.9	5173.9	7232.8
Xinpeng	3767.4	4965.0	8732.4
Xiaozhoushan	1695.4	4578.9	6274.3

TABLE 6 CFs per unit output value of rice-fish culture systems in different villages.

Item		Longxian Village	Xinpeng Village	Xiaozhoushan Village
Rice	Output (kg/ha)	6831.2	7241.6	4954.9
	Output value (*yuan*/ha)	20493.6	21724.8	14864.7
Fish	Output (kg/ha)	318.3	1237.6	187.1
	Output value (*yuan*/ha)	31830.0	123760.0	18710.0
Output value per unit area (*yuan*/ha)		52323.6	145484.8	33574.7
CF per unit output value (kgCO_2-eq/*yuan*)		0.14	0.06	0.19

Xiaozhoushan Village, that is, the environmental impact of obtaining unit output value is smaller than that of Longxian Village and Xiaozhoushan Village.

In this study, the CF per unit output value is used to quantitatively characterize the resilience of IAHS. The larger the CF per unit output value, the lower the resilience of IAHS, and the smaller the CF per unit output value, the higher the resilience of IAHS. Results showed that the CF per unit output value of the rice-fish culture system in Xinpeng Village was the smallest, followed by Longxian Village and Xiaozhoushan Village. This means that in coping with and adapting to the challenges of modernization, the rice-fish culture system in Xinpeng Village has reached a more desirable state and shown a higher resilience, followed by Longxian Village, and the rice-fish culture system in Xiaozhoushan Village has shown a lower resilience though having also reached a relatively desirable state.

4 Discussion

4.1 Effects of conservation and development policies on IAHS resilience

In the context of modernization, how to conserve and manage heritages has become a critical question. Experiences from the World Cultural Heritage indicate that the main objective of heritage management must be to improve people's quality of life and social interaction (Provenzano et al., 2016) and good management may have mid and long-term socio-cultural and economic impacts (Quintana et al., 2022). On the contrary, unsuitable management will result in the destruction of the heritage. For example, Ifugao terraced landscape in the Philippines was destroyed due to unsustainable tourism development (Bantayan et al., 2012). It's also true for IAHS. People increasingly recognize that effective conservation and management plays a very important role in maintaining the sustainability of IAHS, as their vulnerability will make many processes irreversible, and once damaged, it will inevitably lead to the loss of their functions and value (Jiao et al., 2020; Reyes et al., 2020). Moreover, since IAHS are alive systems, their conservation must be conducted in a dynamic way so that local farmers can benefit from the heritage conservation while the heritage site can seek sustainable development (Koohafkan and delaCruz, 2011; Min et al., 2016). Therefore, formulating effective conservation and management strategies or policies plays a key role in helping IAHS respond to the challenges brought by modernization.

The case study of QRFCS shows that although different conservation and development policies were adopted by different villages, they all played an important role in promoting the rice-fish culture system to adapt to modernization and reach a desirable state. Longxian Village, located in the core area, adopted a development strategy with heritage conservation as the core. The conservation planning and subsidy policies changed the governance system originally based on traditional knowledge and culture, and guided farmers to moderately expand the rice-fish culture area and develop small-scale experiential tourism, thus well maintaining the traditional rice-fish culture system. Xinpeng Village adopted a development strategy of expanding the scale of fish farming, which introduced modern technologies into the governance system and created a new action situation. Under the technical support, farmers have successfully expanded the scale of fish farming and obtained considerable incomes by selling fish products. Xiaozhoushan Village took the advantage of terraced landscape and adopted a development strategy focusing on terrace tourism. Supported by tourism development policies, farmers directly or indirectly gained the benefits from tourism management, which attracted more farmers to engage in terrace agriculture. The rice-fish culture system in Xiaozhoushan Village has therefore reached a desirable state in which rice-fish culture and terrace tourism are integrated with each other.

The introduction of conservation and development policies has changed the governance system, but it does not mean the original subsystems have lost efficacy. On the contrary, in the new governance system, the subsystems of traditional culture and traditional knowledge have been further developed and utilized, playing an important role in coping with the challenges of modernization. In both Longxian and Xiaozhoushan villages, traditional culture has made the local tourism development more attractive. Farmers made full use of the local food culture, and served local specialties to tourists at the farmhouse restaurants and homestays. The local governments took advantage of local festival customs to organize a series of cultural and tourism activities, which has attracted a large number of tourists. The development of tourism has also promoted the inheritance and transmission of traditional culture. Tourists have not only brought economic benefits to the villages but also deepened the villagers' recognition of the value of traditional culture. Further, tourists' sharing of photos has also greatly improved the popularity of heritage sites and the spread of traditional culture. Traditional knowledge is the core content of QRFCS, which played an important role in maintaining traditional rice-fish culture, expanding the scale of fish farming and developing organic rice-fish culture. In Xinpeng Village, the combination of traditional knowledge and modern technologies has improved the production efficiency of the rice-fish culture system, increased its economic values, and promoted its modernized development.

4.2 Roles of different actors in IAHS resilience maintenance

The multi-stakeholder process is needed for IAHS conservation and management. Governments, farmers and communities, researchers, enterprises, and social organizations are all stakeholders and should participate in the conservation and management of IAHS. After more than ten years of trial and attempt, China has gradually established a "Five-in-One" multi-stakeholder process, which is led by governments, promoted by researchers and driven by enterprises with active participation of farmers and communities and cooperation from social organizations (Jiao and Min, 2017). Due to China's efforts in IAHS conservation, the status and role of local communities have gradually been recognized. Whether in tourism development or in industrial development, communities in heritage sites are getting more and more attention (Zhang et al., 2018; Gao et al., 2021). Other countries have also established multi-stakeholder processes for IAHS conservation, which have also laid emphasis on the community involvement. For example, Japan promoted extensive community participation in IAHS conservation by establishing a benefit-sharing mechanism (Qiu et al., 2014); South Korea promoted communities to become an important actor in IAHS conservation by setting up committees or associations (Seung-Seok, 2014).

In the adaptation process of IAHS to modernization, different stakeholders serve as different actors and play different roles through the multi-stakeholder process. Governments lead the conservation and development of IAHS, as they guide the production and management behavior of farmers and enterprises through the formulation and implementation of policies. Research institutes play a fundamental role by providing technical support for heritage sites and guiding IAHS conservation and development. Enterprises play a supporting role by pumping external funds into heritage sites and providing diversified livelihood options for communities and farmers. The role of communities and farmers is critical and decisive as they are directly involved in the agricultural production, cultural inheritance and tourism development, and they also directly benefit from the achievement of IAHS conservation and development.

In face of threats and challenges brought by modernization, the maintenance or enhancement of the resilience of QRFCS cannot be achieved without the full cooperation of governments, farmers, enterprises, research institutes and other actors. In Longxian Village, research institutes guided governments to formulate conservation planning and subsidy policies, which enabled farmers to make use of the rice-fish culture system appropriately while maintaining it at a desirable state. In Xinpeng Village, research institutes cooperated with governments to provide technical support for fish farming, and farmers achieved high economic revenues from rice-fish culture by successfully expanding the scale of fish farming. This has provided practical experience for the combination of modern technologies and traditional knowledge. In Xiaozhoushan Village, governments provided supportive policies for tourism development, enterprises brought external funds for tourism development, and farmers participated in terrace tourism and organic rice-fish culture under the support of these policies and funds. Results show that different actors have maintained the QRFCS at a desirable state and helped it adapt to modernization through mutual cooperation and interaction.

4.3 Implications for the conservation of QRFCS

Xinpeng Village formed the development model centering on the enlarged-scale fish farming, which has realized the modernized development of rice-fish culture, brought farmers considerable economic benefits, and achieved a relatively high resilience of the rice-fish culture system. Interestingly, this result indicates that sometimes policies designed to respond to modernization in effect promote modernization, as modernization can also be policy-driven. Meanwhile, this also suggests, under the requirements of dynamic conservation, some intensive-led production or structural adjustments are to some extent beneficial for IAHS conservation and supposed to be promoted in a moderate way. However, in the current development model, high output often means high input. Due to the expanded scale of fish farming, the agricultural production input of rice-fish culture in Xinpeng Village increased significantly, which caused a big increase in CF, and brought environmental risks to a certain degree. In addition, some studies reveal that when the fish output is too high, the nutrient concentrations in the water of paddy fields will increase significantly, and the risk of non-point pollution will also increase (Ma et al., 2020). To achieve sustainable development and maintain the high resilience of the rice-fish culture system, Xinpeng Village must find a balance between economic output and environmental risks. On the one hand, an appropriate scale of fish farming should be determined in a scientific way to reduce the environmental impact; on the other hand, farmers should be encouraged to adopt green and low carbon farming technologies in the rice-fish culture.

Although the rice-fish culture system was maintained through moderate-scale land management in Longxian Village, its economic benefits were low due to the low output of fish. The decrease in fish output also interfered with the symbiosis relationship between rice and fish and therefore affected the growth of rice. In order to improve the rice yield, farmers had to increase the fertilizer input, which made the rice-fish culture system have a higher CF and therefore show a lower resilience. The maintenance of the rice-fish culture system in Longxian Village is largely supported by subsidy policies, however, this is not conducive to the long-term sustainable development due to the low economic benefits. Therefore, we suggest Longxian Village moderately increase the scale of fish farming, which can improve the economic output of the rice-fish culture system as well as its resilience and help maintain the reciprocal relationship between rice and fish. Further, the current subsidy policies should be optimized and adjusted to promote farmers to carry out green and organic production to achieve the win-win goal of economic and environmental benefits by improving product values.

The development of terrace tourism is an innovative approach for the conservation and development of the rice-fish culture system, especially in a situation where the traditional restaurants catering tourism is losing its appeal (Zhang C. et al., 2017). However, due to the tourism development, the fish farming gets ignored in Xiaozhoushan Village, which makes the rice-fish culture system in a state of low input and low output. Therefore, although the organic rice-fish culture in Xiaozhoushan Village had the lowest CF, it had the highest CF per unit output value and indicated the lowest resilience. Despite the policy and financial support, the sustainability of the rice-fish culture system in Xiaozhoushan Village is a concern in the long run. Local governments and enterprises need to realize that without the sustainable development of agriculture, the terrace tourism will lose its appeal finally. The sustainable development of agriculture not only emphasizes the reduction of environmental impact, but also needs the support of stable economic benefits. Xiaozhoushan Village must moderately expand the scale of fish farming, increase the fish output of the rice-fish culture system and find ways to increase the price of organic rice in the market.

4.4 Strengths and weaknesses of the research methods for IAHS resilience

The evolution history of many hundreds of years has proved that when facing internal or external disturbance, IAHS showed remarkable traits of resilience, making them adapt to the disturbance and achieve a new equilibrium (Fuller et al., 2015; Jiao et al., 2016). However, the resilience of IAHS involves many influencing factors, which makes its accurate description and assessment become a difficult point in IAHS research. In this study, we incorporate IAHS resilience into the SES framework and put forward a SES-based analytical framework for IAHS resilience, which is an innovation for IAHS research. The application in QRFCS demonstrates that the SES-based analytical framework can reveal the interaction process between the subsystems of QRFCS driven by conservation and development policies, and further reflect the impact of such interactions on the resilience of QRFCS. The introduction of SES framework not only fills the gap in current IAHS resilience research, but also has good applicability to different heritage systems, which will greatly contribute to the conservation and management of IAHS. At the same time, the proposed analytical framework in this study is also an important expansion of the SES research by incorporating IAHS, a typical representative of social-ecological systems, into the research field, which will largely enrich the theoretical exploration and practical application of the SES research.

Quantitative assessment of resilience is a hot and difficult issue in SES research. In this study, we suggest considering the trade-off among ecosystem services as the surrogate for IAHS resilience. Specifically, the resilience is characterized by quantifying the trade-off between the food production service and one or some other services. This is an innovation for the quantitative assessment of SES resilience. In the case of QRFCS, we attempt to quantify the trade-off between the food production service and the GHG emission reduction service by using the indicator of CF per unit output value. Based on the CF method, the resilience of QRFCS has been quantitatively characterized by the indicator of CF per unit output value and the outcomes of its resilience change have been assessed and compared among different development modes. However, the resilience of IAHS is not only reflected in the trade-off between the food production service and the GHG emission reduction service, but also in the trade-offs between the food production service and other regulating ecosystem services. Therefore, the employment of the indicator of CF per unit output value, though innovative, is not comprehensive enough for assessing the IAHS resilience. Future studies should explore how to consider more regulating ecosystem services, how to use their trade-offs with the food production service to describe the resilience of IAHS, and how to create more indicators to be used together or a more comprehensive indicator to quantify the resilience of IAHS.

The SES-based analytical framework can analyze the complex interactions between subsystems and reveal the adaptation process of the system, but it can hardly measure whether the adaptation is beneficial to the system in a quantitative way. The CF-based evaluation method focuses on the adaptation result of the system and measures the change of the system resilience. However, it is difficult to explain what kind of interaction inside the system has caused such a result. The combination of the two methods compensates for these shortcomings. In the case of QRFCS, the connection between the two methods is found in the changes of farmers' behaviors. Farmers are the most important actors in the conservation and management of IAHS. Under the SES-based analytical framework, though driven by different policies, the interactions between subsystems of QRFCS ultimately achieve the adaptation by influencing the production or business behaviors of farmers. The CF-based evaluation method calculates the resilience indicator based on the survey data of farmers, therefore the assessment results are directly linked to the production or business behaviors of farmers, which forms feedback on the driving policies. The con-joint use of the two methods has effectively combined the process analysis with the result evaluation in the SES resilience research, thus helping managers better understand the adaptation process and result of the SES.

A weakness in the case study of QRFCS is that we only compare the resilience differences among different villages after implementing different policies, without analyzing the dynamics of the resilience of the rice-fish culture system in a specific village before and after a specific policy is implemented. Jiao et al. (2023) found that compared with 2015, both the CF and the output value per unit area of the rice-fish culture system in Longxian Village decreased while the CF per unit output value increased in 2018. In the context of this study, a decreased CF per unit output value means a decline in the resilience of the rice-fish culture system, behind which the reasons are worth exploring. Therefore, future studies should pay more attention to the dynamic changes in the resilience of the rice-fish culture system, so as to have a deeper and more comprehensive understanding of the policy driven adaptation outcomes.

5 Conclusion

Formulating effective conservation and management policies plays an important role in helping IAHS cope with the threats and challenges brought by modernization. Whether these policies are effective depends on whether they maintain or enhance the resilience of IAHS to avoid them falling into an undesirable cycle. In this context, we put forward a SES-based analytical framework for IAHS resilience, to analyze how IAHS adapt to external disturbances under the drivers of policies. Further, we choose the trade-off of ecosystem services as the surrogate of IAHS resilience and use the CF per unit output value born from the CF method as an indicator to quantify IAHS resilience. The application in QRFCS demonstrates that the SES-based analytical framework can better reveal the adaptation process of IAHS driven by conservation and development policies and the CF per unit output value indicator can well measure the effectiveness of these policies by quantify the resilience of IAHS. The SES-based analytical framework for IAHS resilience cannot only enrich the resilience study of SES, but can also promote IAHS management and regional sustainable development. The CF per unit output value indicator, though limited in comprehensiveness, is an innovation for the quantitative assessment of IAHS resilience. More explorations can be done on assessing IAHS and other SES resilience by quantifying the relationships of multiple ecosystem services in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for the studies involving humans because in the Institute of Geographic Sciences and Natural Resources Research, we do not require ethical board approval if we mention the purpose, and get consent from the participants. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements because during the field survey, we clearly mentioned the purpose of the study, data collection methods, data handling, and so on in detail. Before entering the survey, the participants were requested to accept our proposal otherwise they were refused automatically. Furthermore, we did not collect any single individual personal information like name, address, telephone number, and so on.

Author contributions

WJ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. ZY: Formal analysis, Visualization, Writing – original draft. SH: Conceptualization, Funding acquisition, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1364075/full#supplementary-material

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