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Evolution of livelihood vulnerability in rice terrace systems: Evidence from households in the Ziquejie terrace system in China

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Introduction: Globally, terraces, and rice terrace systems face problems that affect their sustainability, such as terrace degradation, abandonment, de-agriculturalization, labor migration, etc. The implementation of development projects such as reforestation, poverty alleviation, and tourism development have changed traditional smallholder livelihood patterns. It is not clear whether farmers' livelihoods have become more resilient or vulnerable as a result.

Methods: Using survey data on households' livelihoods in a rice terrace system in Southern China, we evaluated the livelihood impacts of multiple changes.

Results: The results show that development projects are not entirely beneficial. The attributes and intensity of the disturbance of projects (e.g., tourism) on land functions, and differentiated farmer strategies jointly drive the hierarchical evolution of livelihood vulnerability. In detail, underdeveloped tourism increased rather than reduced livelihood vulnerability; the role of agriculture in livelihood directly exacerbated the variation in vulnerability levels; this resulted in the most vulnerable livelihood for households that are exogenously dependent or located in the core tourism area.

Discussion: Subsequently, an evolutionary model of livelihood vulnerability is proposed in this study. Based on this, we judged that the livelihood vulnerability of rice terrace systems has entered a chaotic stage of adaptation. Reducing livelihood vulnerability will require the support of a tangible and circular pathway of benefits between farmers and the land. Policies should focus on the heterogeneity of farmers and the "negative effects" of development projects on livelihood. This household-level farmer livelihood vulnerability dynamics study goes beyond anti-poverty to provide science-based practical guidance to promote the sustainable development of rice terrace systems.

KEYWORDS

livelihood vulnerability, rice terrace, dynamic evolution, land, tourism, agricultural cultural heritage system

1. Introduction

Terraces are stepped fields built along contours on hills or mountains that are ideal for early human settlement and agricultural activities (Stanchi et al., 2012; Deng et al., 2021). Terraced farming is the main source of livelihood for most hillside farmers worldwide (Chapagain and Raizada, 2017). In China, the 58.46 $\pm$ 2.99 Mha of terraced land accounts for one-third of the country's agricultural land area (Cao et al., 2021; Wei et al., 2021) and provides a wide range of ecosystem services (ESs), such as food provisioning, hydrological regulation, biodiversity maintenance, carbon sequestration, and nutrient cycling (Wei et al., 2012). Rice terracing systems (RTSs) are widely distributed in the subtropical hilly areas of east and southeast Asia. RTSs are recognized and protected globally as the basis for sustainable management because they couple subsistence, natural landscapes, and agricultural civilization. Several ancient rice terraces are listed by the Food and Agriculture Organization of the United Nations as globally important agricultural cultural heritage systems (GIAHS) (FAO, 2018).

In recent years, human-land conflicts have threatened the sustainable development of rice terrace systems. The low efficiency of terracing has led to land degradation and abandonment, de-farming, migration of agricultural labor, and aging (Mori et al., 2019). Valuable ecosystem services are gradually diminishing and human welfare is being undermined (Sarker, 2020). Some studies point to the widespread destruction of agroecosystems and terraced landscapes as the reason for the unsustainability of terrace systems. Field-scale studies of environmental mechanisms, such as rice soil nutrients (Gao et al., 2016), microorganisms (Sun et al., 2018), and water supply and demand, provide a reference for optimizing terraced agricultural management practices. Researchers have tried to reconstruct the relationship between historical terraced environments and human activities based on soil geochemical analysis (Jiang et al., 2017) and social institutional systems (Araral, 2013). This may help explain why rice terrace systems are currently unsustainable despite having persevered through major natural and historical transformations. Studies on ecosystem services, adaptability, and resilience offer possible directions for the future development of rice terrace systems (Lansing et al., 2017; Aguilar et al., 2020). In traditional rice terrace systems that depend on natural resources for survival, "livelihood" is the human-land bridge. Some researchers argued that improving the livelihood of farmers through government conservation and development projects can contribute to the sustainable development of the rice terrace systems. For example, policy tools to sustain and improve terraced agriculture (Chapagain and Raizada, 2017) and multistakeholder landscape conservation mechanisms can increase the income of farmers (Zhang et al., 2019). Farmers' livelihood systems are an important part of the coupled human-land system. However, studies of livelihood vulnerability as one of the cores of sustainability research in coupled human-environment systems are still lacking (Turner et al., 2003). It is not clear whether farmers' livelihoods become more vulnerable or resilient in the context of complex change.

Vulnerability terminology was introduced into the analysis of poor farmers' livelihoods in the third IPCC report (IPCC, 2001). Livelihood vulnerability is the degree to which livelihoods are vulnerable to perturbations and capable of transforming risks to mitigate adverse impacts (Chamber and Conway, 1991; DFID, 2000). Livelihood vulnerability studies provide realistic assessments of conceptualized human wellbeing, its actual access, exposure or vulnerability to damage, and the ability to recover. On a larger scale, the livelihoods of farmers in developing countries exhibit different vulnerabilities to external risks, such as climate and land-use change and ecological degradation (Martin et al., 2016; Wenyu et al., 2017; Zhang et al., 2018; Nguyen and Leisz, 2021). At the regional scale, the impacts of socioeconomic factors such as urban land acquisition, economic fluctuations, pro-poor policies, and tourism development on livelihood vulnerability have been studied (Huang et al., 2017; Wang et al., 2018, 2020; Li et al., 2020). Conceptual analytical frameworks have been constructed and quantitative assessment methods (such as the Livelihood Vulnerability Index) have also been applied (Hahn et al., 2009; Reed et al., 2013; Gerlitz et al., 2016; Recanati et al., 2017). Livelihood vulnerability in the context of climate change can be affected by the interaction of multiple stressors, such as biophysical and socioeconomic conditions (Unks et al., 2019). However, studies that quantitatively identify key pressures on livelihood vulnerability in different contexts are still lacking. The traditional livelihood patterns of rice terrace systems have changed in the internal and external dynamics of policy renewal, land use change, and population migration. There have been studies that start with farmers' livelihood capital. They focused on the different responses to agricultural conservation actions by farmers with different livelihood endowments in the RTS (Liu et al., 2018). Land capital positively influences farmers' perceptions of livelihood support, and an increase in the level of cultural assets is key to achieving dynamic adaptation of livelihood (Yang et al., 2018). But it is not known how environmental change affects livelihood capital and farmer response. How exactly do area development, land and farmers relate to livelihood vulnerability dynamics? Whether livelihood vulnerability has an evolutionary pattern similar to the overall vulnerability of complex systems is unclear (McDowell and Hess, 2012; Unks et al., 2019). Therefore, it is of practical and scientific importance to explore the dynamic evolutionary mechanisms of livelihood vulnerability in the rice terrace system.

Based on this, we selected a typical ancient millennium rice terrace system (the Ziquejie terrace system in China) as the study object. We ask ourselves, how the trend of tourism development in rural areas and rural revitalization policies interfered with the function of the land in the Ziquejie terrace system? How has the livelihood environment of farmers been impacted as a result? Whether dynamic adaptation of the rice terrace system can be achieved by reducing farmers' livelihood vulnerability is urgently needed to be studied. Using a vulnerability framework, we identified the level and characteristics of livelihood vulnerability and its drivers of the Ziquejie terrace using households as the unit of analysis. This revealed how disturbances in rice terrace systems, changes in land function, and farmer strategies have jointly driven the evolution of livelihood vulnerability stages. An evolutionary model of the livelihood vulnerability that can be referenced and applied was finally developed. This will provide a reference for promoting sustainable development of similar rice terrace systems or even other smallholder systems in mountainous areas.

2. Study area and data source

2.1. Study area

The Ziquejie rice terraces are located in the middle section of Fengjia Mountain in the Xuefeng Mountain Range, in the town of Shuiche, southwest Xinhua County, Hunan Province, China (110°52′-111°00′E, 27°28′-27°45′N). Its altitude is 500–1,200 m above sea level with a slope of 30–50°. The area has a subtropical monsoon climate, with an average annual temperature of 13.7°C and an average annual rainfall of 1,643 mm. The terraces originated in the Qin and Han dynasties and were developed during the Song and Ming dynasties. The Miao, Yao, Dong, and Han ethnic groups have made their living here for millennia by

Abbreviations: RTS, rice terrace system; GIAHS, Globally important agricultural heritage systems; In figures and tables: Abbreviations for all indicators are explained in Table 1.

TABLE 1 Indicator system for assessing the livelihood vulnerability of rice terrace system.

Dimensions	Sub-components	Code	Indices	Units	Directional	Weights
Sensitivity	Agroecosystem	F	Fertilizer application intensity	Kg	–	0.002
		Dry	The proportion of arid paddy fields	%	–	0.007
		OF	Organic agriculture	%	+	0.059
	Rural social system	DR	Dependency ratio	%	–	0.002
		MW	The proportion of migrant workers	%	–	0.015
		PD	Population with major diseases	Individuals	–	0.008
		Age	The average age of the left-behind labor force	Year	–	0.003
	Household economic system	IPD	Per capita disposable income	Yuan	+	0.025
		IPI	The income proportion of the primary industry	%	–	0.003
		TR	The proportion of tourism revenue	%	+	0.212
		IMW	The proportion of migrant workers' income	%	+	0.012
		LR	The local income	Yuan	+	0.118
		IA	Sustenance of livelihood	%	–	0.030
Responsive capacity	Self- effort	TP	Tourism participation	%	+	0.101
		NLA	Diversity of livelihood	Nunber	+	0.017
		PSS	Level of education	%	+	0.033
	External support	FS	Fiscal subsidy	Yuan	+	0.085
		SSS	Subsidies of scenic spots	Yuan	+	0.266

growing rice. They took advantage of the terrain and climatic conditions to build terraces and artesian irrigation systems. The landscape pattern incorporates rice terraces, forests, rivers, and villages reflecting the wisdom of ancient farmers to live in harmony with nature (Figure 1). In 2018, it was listed as a globally important agricultural heritage system (GIAHS) by the FAO, together with the Youxi United, Longji, and Chongyi Hakka terraces (FAO, 2018). Based on government statistics and our fieldwork interviews, we obtained more information about the Ziquejie terrace system. It has been recognized as a national AAAA tourist attraction and World Irrigation Engineering Heritage Site. The fragmented terraces prevented the mechanization and intensification of traditional smallholder farming practices. The low efficiency of the terraces has led many young and middle-aged laborers to engage in migrate or engage in off-farm work. According to the town government's agriculture and natural resources management department, the total degraded area of terraces by 2020 after treatment is 80 hm^2, accounting for 4% of the total area of terraces in the core scenic area. This shows that the sustainability of terraced agriculture is being threatened. In addition, the Ziquejie terrace system is originally part of a national poverty-stricken county. A series of national poverty alleviation measures such as subsidies for health care, education, and entrepreneurship are implemented here. Multiple disturbances such as tourism development, poverty alleviation policies, and infrastructure have changed the livelihood environment of the Ziquejie terraces. The state of land function and farmer livelihood vulnerability in response to disturbances is unclear. In this context, the study of livelihood vulnerability and evolutionary patterns will provide a reference for addressing the dilemma of farmers' livelihoods and achieving dynamic adaptation in the Ziquejie terrace system.

2.2. Data source

In this study, we used participatory rural appraisal (PRA) and GIS technology to obtain data. PRA was used for household surveys and semi-structured interviews. This method is often used to survey rural resources, livelihoods, and other relevant farm household data to obtain farmers' responses and perceptions of economic, resource, and ecological changes (Xi et al., 2015; Tu et al., 2018). We recorded the GPS data of the survey sample points superimposed on the DEM digital elevation map to facilitate the collation of information on the spatial location, elevation, and distance from the town of the interviewed households (Figure 2). The investigation procedures were as follows: (1) The questionnaire design was preceded by a one-week a priori visit in October 2020. We designed questionnaires and interview outlines based on the survey results and research objectives. (2) Before the official survey, we selected 10 households as a trial. The questionnaire was adjusted and improved after the pilot survey. (3) Survey team members were intensively trained. Respondents were selected based on the following: (1) the sample villages were all located within the scenic area of the Ziquejie terrace system; (2) To ensure the randomness of sample selection, we only determined the sample size without determining the attributes and locations of the samples in advance. We conducted the formal survey between July and August 2021. Finally, we selected ten villages in the Ziquejie terrace system and randomly selected 240

FIGURE 1
(A) Landscape pattern; **(B)** Self-sustaining irrigation system; **(C)** Organic farming with rice, fish, and ducks; **(D)** Human landscape.

interviewed households. Among them, 223 questionnaires were valid, accounting for 95.7%. The average distribution rate of the sample households in the villages was 3.36%. The main contents of the questionnaire included basic information about family members, terracing and agricultural production, employment and income, tourism participation, government compensation, social security, and personal perceptions. In addition, we conducted semi-structured interviews with local stakeholders including the agriculture department, natural resources department, village cadres, scenic area management office, and agricultural cooperatives. The content covered agricultural development data, government management measures, and scenic spot development programs.

3. Methodology

3.1. Construction of index system

Indicator evaluation methods can accurately explore the manifestations and causes of livelihood vulnerability (Zhao, 2017). One type of index system uses poverty as a proxy for household welfare, measuring the sensitivity to or unaffordability of environmental change based on changes in household poverty status (Padda and Hameed, 2018; Deng et al., 2020). Another type integrates the indicators of the biophysical impacts of environmental change (exposure) with socioeconomic characteristics (sensitivity and response). In this study, livelihood vulnerability is the susceptibility of rice terrace system livelihoods to negative impacts from tourism development, and changes in land function. We constructed the evaluation system using the IPCC concept of vulnerability, which is a function of exposure, sensitivity, and responsiveness (Smit and Wandel, 2006). The attributes of exposure and sensitivity in households are difficult to separate because both are subject to interactions between system characteristics and the stimulus attributes of environmental change (Luers, 2005; Huang et al., 2017). Therefore, we constructed the indicator system with two dimensions: sensitivity and response.

3.1.1. Defining the sensitivity index

The indicator variables of sensitivity should reflect the vulnerability of a system to adverse or favorable stimuli from environmental change (Gallopín, 2006). Occupancy characteristics reflecting a wide range of biophysical and socioeconomic contexts

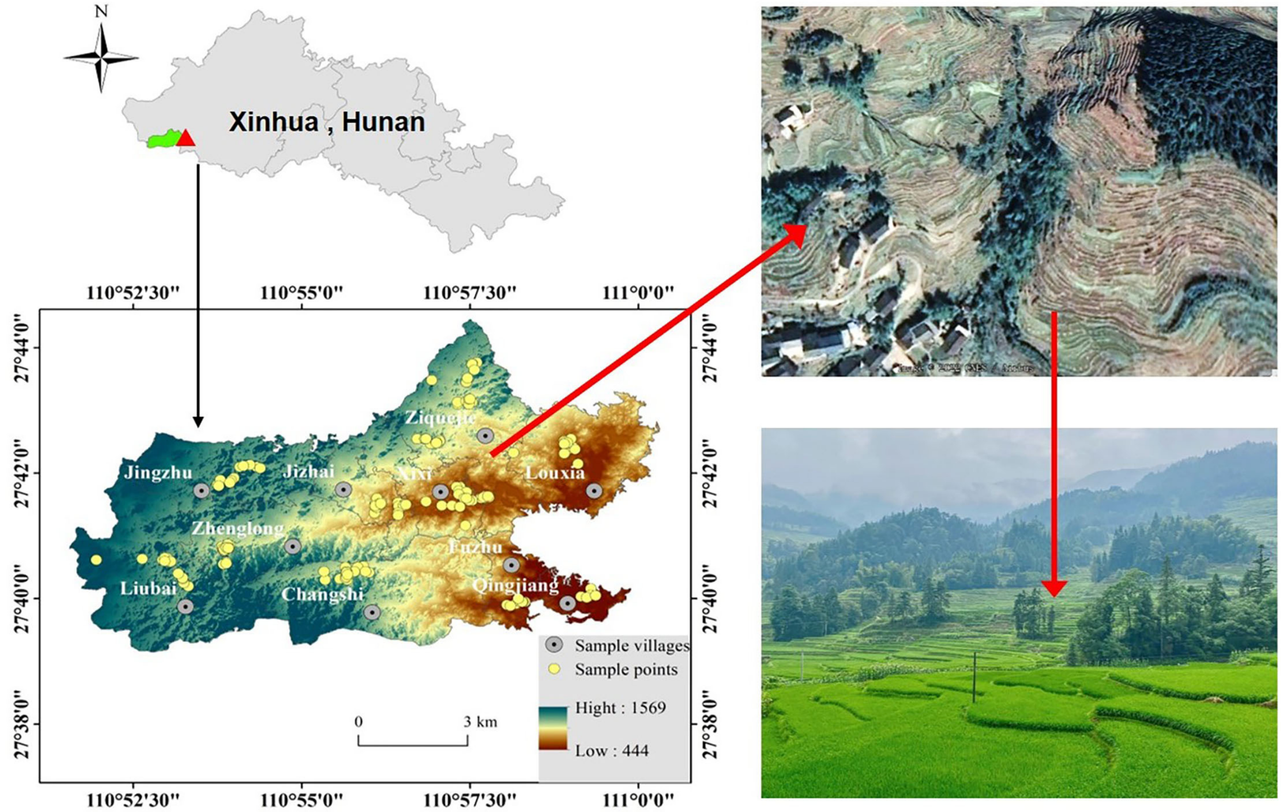

FIGURE 2
Location of the study area and sample sites.

(e.g., settlement type and location, land use, and livelihood structure) are sometimes referred to as sources of exposure/sensitivity (Smit and Wandel, 2006). Universal indicators include variables such as ecological security, climate, topography, GDP, or other types of capital (technology, education, infrastructure, etc.) (Hinkel, 2011).

Social and policy renewal has changed the sources, levels, structures, and risk environments of smallholder livelihoods in the Ziquejie terraces. Thus, we primarily selected aspects that interfere with farmers' livelihoods to measure dynamic sensitivity. For example, we specifically selected tourism-related indicators to measure the impact of development projects on livelihood vulnerability. In detail, the level and source of livelihood are measured by disposable income per capita, external and local income (spatial sources), and income from primary and tourism industries (industrial sources). Endogenous household pressures (e.g., dependency burden, aging workforce, and household health) influence livelihood structure and farmer strategies through labor and savings levels. Livelihood replenishment capacity is used to measure the ability of livelihoods to recover from stress. Eventually, we integrated three subdimensions (agroecological, rural society, and household economic systems) to evaluate sensitivity.

3.1.2. Defining the responsiveness index

Responsiveness at the national level relies on well-developed social infrastructure and mechanisms rather than on the level of economic activity (Gallopín, 2006; Ifejika Speranza et al., 2014). Regional responsiveness is more likely to be related to the ability to access and manage resources such as finance (e.g., state-subsidized crop insurance), technology, and information (Adger et al., 2004; Adger, 2006). Whether development projects and policies in the Ziquejie terrace affect livelihood vulnerability through farmer responsiveness is not known. For example, pro-poor policies increase livelihood sustainability but do not necessarily reduce vulnerability (Deng et al., 2020). External support such as terraced landscape conservation, employment, and compensation for land acquisition directly affected farmers' livelihood strategies. Tourism participation indicates that farmers' livelihood strategies respond positively rather than conservatively to development projects. Livelihood diversity and educational attainment reflect whether farmers have multiple pathways and strategies to cope with environmental change. Thus, individual effort and external support are sub-dimensions that measure the responsiveness of farmers' livelihood on the Ziquejie terrace (Table 1).

3.2. Approach

(1) Standardization of the data. Given the different scales and magnitudes of the indicators, we needed to standardize the initial value, which was performed using the method described in

TABLE 2 Descriptive statistics of the survey sample.

	Self-sufficiency	Self-Irrigation	Organic agriculture	Migrant workers	Participation in tourism
Number	197	192	113	196	61
Proportion	88.34%	86.10%	50.67%	87.89%	27.35%
	Per capita cultivated area	Arid field	Paddy fields become dry fields	Returning farmland to forest	Man-made abandonment
Area	0.0533 hm²	328.1	118.4	160.8	48.9
Proportion		32.85%	36.09%	49.01%	14.90%

In this table, the statistics describing the livelihood strategies and land ownership status of farmers, present the overall livelihood characteristics of those working in the rice terrace system in Ziquejie.

Equation (1).

$$X_{ij}^{'} = \frac{X_{ij} - X_{jmin}}{X_{jmax} - X_{jmin}}$$
$$X_{ij}^{'} = \frac{X_{jmax} - X_{ij}}{X_{jmax} - X_{jmin}} \quad (1)$$

where $X_{ij}^{'}$ is the standardized value of the index; X_{ij} is the original value of the indicator; X_{jmin} and X_{jmax} are the minimum and maximum values of each indicator, respectively; i is the number of the sample, and j is the serial number of the indicator.

(2) Determination of weights. In this study, we used the entropy weighting method in Equation (2) to calculate the weights of each indicator.

$$W_j = \frac{d}{\sum_{j=1}^{m} d}$$
$$d = 1 - \{\sum_{n=1}^{222} P_{j\times} \ln(P_j) \times [-\frac{1}{\ln(n)}]\} \quad (2)$$

where W_j is the weight of the indicator, m is the number of indicators, n is the number of samples, d is the coefficient of variation of the indicator, and P_j is the eigenvalue of the indicator.

(3) Evaluation of livelihood vulnerability.

$$LVI = \frac{SI}{RI} \quad (3)$$

For the livelihood vulnerability index (LVI), the higher the value, the higher the livelihood vulnerability of the farmer; SI is the sensitivity/exposure; RI is the responsiveness index. We calculated SI and RI using a weighted summation method.

$$SI = \sum_{j}^{13} W_{sj} X_{sij}^{'}$$
$$RI = \sum_{j}^{5} W_{Rj} X_{Rij}^{'} \quad (4)$$

where W_{sj} and W_{Rj} are the weights of the sensitivity and responsiveness indices, respectively; $X_{sij}^{'}$ and $X_{Rij}^{'}$ are the normalized values of the sensitivity and responsiveness indices, respectively.

(4) Differentiation study. We used a combination of spatial classification and algorithm-based K-means clustering to analyze the livelihood vulnerability characteristics of farm households in different spaces and livelihood types. The spatial classification is based on the local tourism development plan map obtained in semi-structured interviews. The core and peripheral areas overlap with the core scenic area-peripheral scenic area of the tourism plan, respectively. The two classification results were tested by independent samples *t*-test and one-way analysis of variance (ANOVA).

(5) Factors influencing livelihood vulnerability. We performed principal component analysis (PCA) to explore the causes of livelihood vulnerability under different criteria of farming household differentiation outcomes to identify the key drivers of characteristic differentiation.

4. Results

4.1. Overview of livelihood characteristics

Table 2 shows that the arable land per capita in the Ziquejie terrace system is 0.0533 hm², the food self-sufficiency rate is 88.34% and the irrigation self-sufficiency rate is 86.1%. Organic farming traditions are still maintained by more than half of the farming households even though 32.85% of the surveyed rice fields have dried (fallow to the forest, conversion of paddy fields to dry land, and artificial abandonment). This suggests that 1,000-year-old terraced agriculture still plays a fundamental role in the livelihoods of farmers in the Ziquejie terraces. Compared with the ordinary terrace system, the abandonment rate of terraces under the high (87.89%) outworking rate is not very high. The reason for this may be the lower time cost of single-season rice production under artesian irrigation systems. This has led to the emergence of livelihood types that combine terraced agricultural production with off-farm work. Tourism development and ecological conservation have changed the function of the land on which farmers depend. The land provides landscape and cultural values for livelihoods in addition to past agricultural production and habitat maintenance. However, the tourism participation rate of only 27.35% indicated that tourism is not currently offering effective support for livelihoods in the Ziquejie terrace system. Instead, the livelihoods of some farmers have become more vulnerable due to the transfer of the value of public resources. In short, the original livelihood stability of the Ziquejie terrace has been disrupted.

4.2. Livelihood vulnerability differentiation

After spatial classification, the core area includes six villages Ziquejie, Xixi, Jizhai, Zhenglong, Changshi, and Louxia Village. The peripheral area includes Jingzhu, Liubai, Fuzhu, and Qingjiang

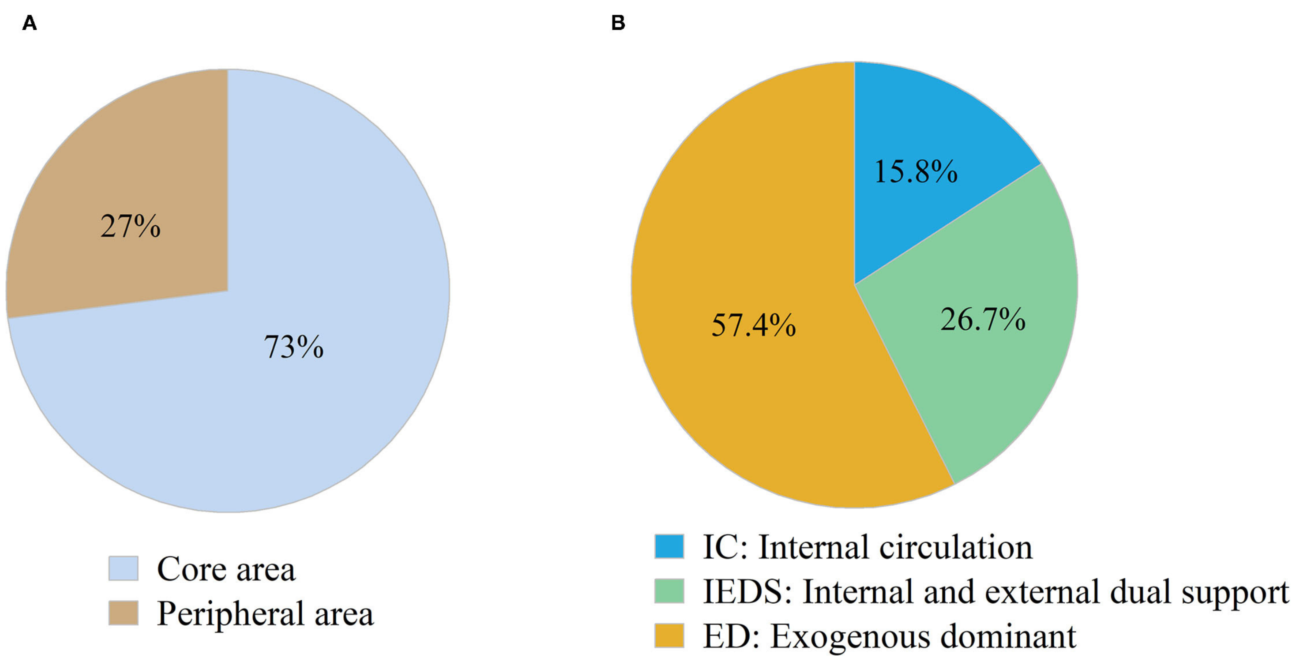

FIGURE 3
Results of household classification using two standards: **(A)** the weight of the core and peripheral areas in the spatial classification; **(B)** the weight of each of the three farmer types.

villages. The proportions of the core and peripheral areas were 73 and 23%, respectively. In terms of type, we used K-means clustering to delineate three farm household livelihood types, representing 15.8, 26.7, and 57.4% each (Figure 3). They are A: internal circulation type (IC), dependent on local livelihoods; B: internal and external dual support (IEDS), combining local agriculture, off-farm work and seasonal migration, and C: exogenous dominant (ED), relying on migrant work; Table 3 shows that both SI and RI were statistically different under the two classification results.

4.2.1. Spatial heterogeneity of livelihood vulnerability

The results of the analysis showed that the spatial pattern of livelihood vulnerability in the Ziquejie terrace system was high in the core tourist area and low in the periphery (Figure 4). All three indices (LVI, SI, and RI) were higher in the core than in the periphery, indicating that livelihoods were more vulnerable in the core than in the periphery with the severity of 23.07% (Figure 4). The two dimensions of SI and RI are clearly differentiated, with the former having a larger coefficient of variation.

The spatial variation in sensitivity was mainly reflected in farmers' livelihood dependence on local tourism and outworking. (1) The core area has a higher share of the primary sector, tourism, and local-source incomes. Those in the peripheral area had a higher share of income from migrant labor, even though they were further away from the towns than the core area (Figure 5). This suggests that farmers' livelihood in the core area may be more vulnerable to local environmental changes than in the peripheral area. The tourism income outliers represent only a limited number of households in the core area that enjoy the dividend of development projects. (2) The drought rate in the core area was lower, but the intensity of fertilizer application was higher (Figure 5). Collectivized terraced management (e.g., land transfer to agricultural cooperatives) controls artificial abandonment and land degradation. But this is more likely to expose the livelihood of farmers in the core area to the risk of agro-ecological destruction.

Differences in responsiveness were reflected mainly in tourism participation and livelihood diversity. (1) Tourism participation was remarkably higher in core areas than in peripheral areas (Figure 5). This is due to the rich and continuous terraced landscape in the core area. (2) Livelihoods in the peripheral area is more diverse because of the higher level of education of farmers (Figure 5). Yet they are rarely involved in the local tourism industry. A simple increase in the number of livelihoods can be considered a weak response to disturbances. Thus, limited participation in tourism has led to low responsiveness in the peripheral area (Figure 4).

In summary, tourism development dominates the spatial variation in livelihood vulnerability of the Ziquejie terrace system. This difference stems from the contribution of land resources to livelihood and the extent to which they are disturbed by tourism.

4.2.2. Structural heterogeneity of livelihood vulnerability

The results of the analysis showed that the levels and characteristics of livelihood vulnerability were different for the three types of farmer groups (Figure 6).

i. **Group IC:** Moderately vulnerable-highly sensitive-highly responsive.

TABLE 3 Significance test of the difference between groups after cluster analysis.

	Independent sample *T*-test			ANOVA			
Variable	*t*	*df*	Sig.	*df*	Mean square	*F*	Sig.
SI	2.241	197.883	**	2	0.642	166.815	***
RI	3.624	180.415	***	2	0.060	8.470	***
LVI	0.585	200.625	*	2	53.324	0.140	*

*, **, ***Significance at 10, 5, 1%, respectively. The results of the statistical tests for cluster analysis. According to the split in the first row (left) the results of the independent sample t-test for spatial classification and (right) the results of the one-way ANOVA test for the K-means cluster analysis for type classification.

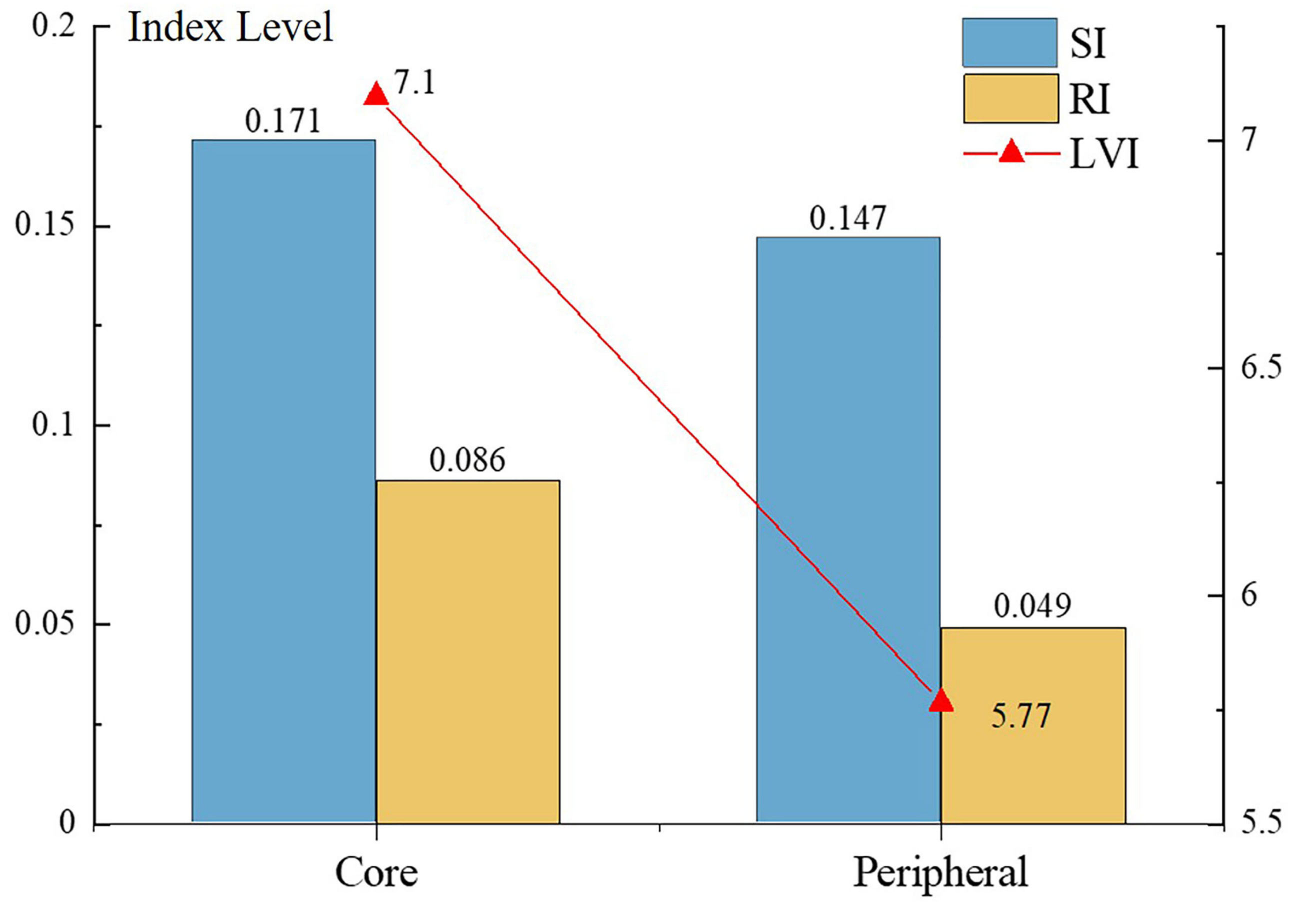

FIGURE 4
Spatial variation in livelihood vulnerability levels and characteristics. Blue and yellow bars indicate differences in sensitivity and responsiveness, respectively; red line segments indicate differences in livelihood vulnerability levels. The horizontal axis indicates spatial grouping, the left vertical axis represents the level of the sensitivity and responsiveness index, and the right vertical axis represents the level of the livelihood vulnerability index.

Group IC is a local tourism beneficiary group. Their livelihoods depended on tourism and local non-agricultural industries. The benefit-oriented transformation of livelihood strategies has led to higher a ratio of drought cultivated land and lower participation in green agriculture in this group (Figure 7). The tourism industry which is based on the liquidity of the system is prone to external environmental influences (such as weather, infectious diseases, regional policies, publicity, etc.) and is full of uncertainties. The IC group, whose livelihood is entirely dependent on tourism, has been forced to expose itself to instability. Higher responsiveness still does not counteract sensitivity to uncertain risks of ecological damage to tourism and agricultural landscapes.

ii. **Group IEDS:** Mildly vulnerable-moderately sensitive-moderately responsive.

This is a special but not the main type of livelihood on the Ziquejie terraces. It combines agriculture and non-agriculture, local and non-local, and participates positively in tourism development. The lowest drought rates and high organic farming rates guarantee high quality agroecological environment (Figure 7B). Of course, this is relevant to the structure of the household workforce, such as number, age, and health (Figure 8). They are exposed to multiple risks while enjoying multiple sources of livelihood. This elicited a sensitivity comparable to that of the IC group. The highest livelihood diversity and educational attainment may have resulted in the

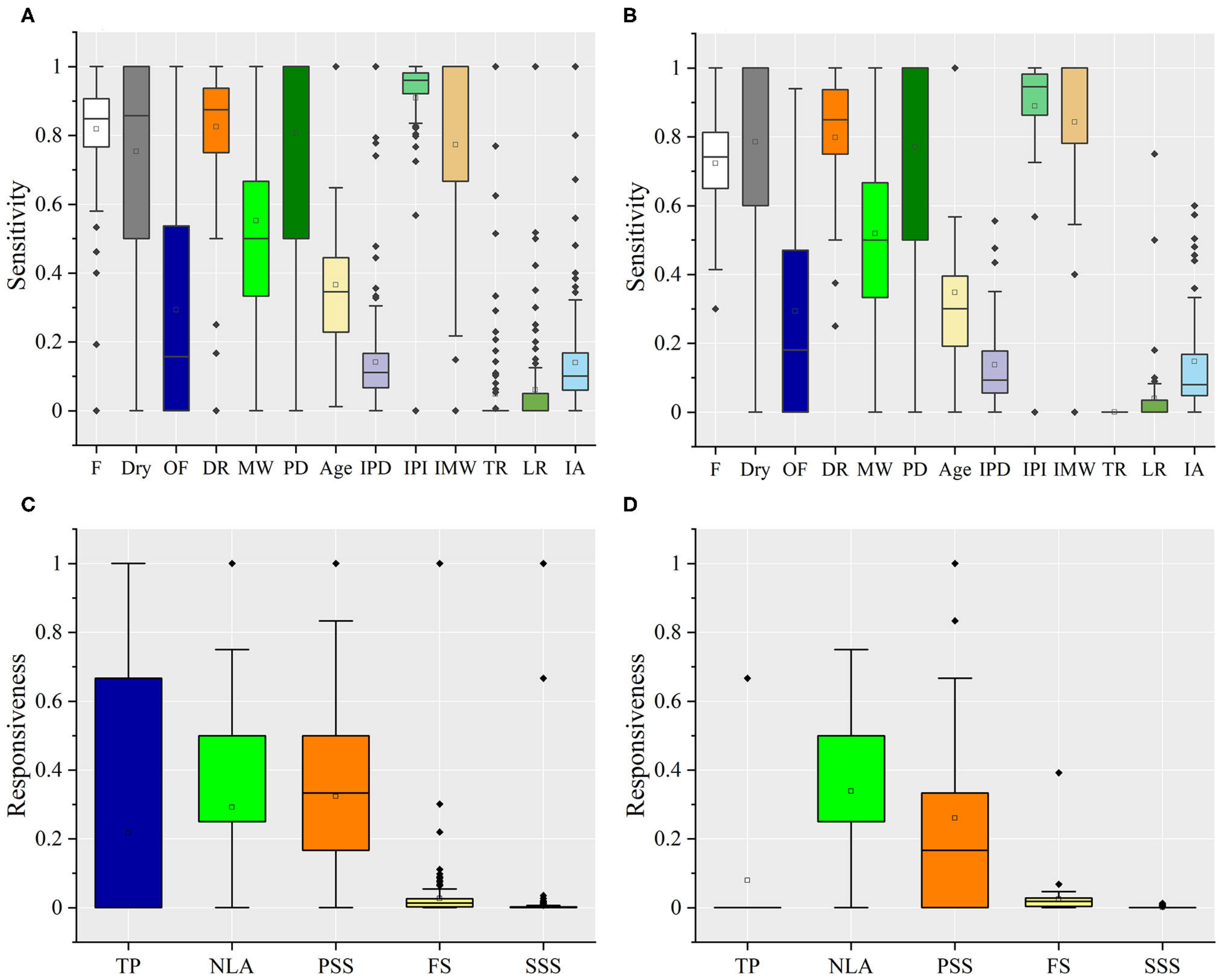

FIGURE 5
Differences in subdimensions of farm households in core and periphery areas. **(A, B)** The sensitivity indicators for livelihoods in the core and peripheral areas, respectively; **(C, D)** indicators of the responsiveness of the core and peripheral areas, respectively. The abbreviations all correspond to the interpretation of the indicators in the indicator system in Table 1.

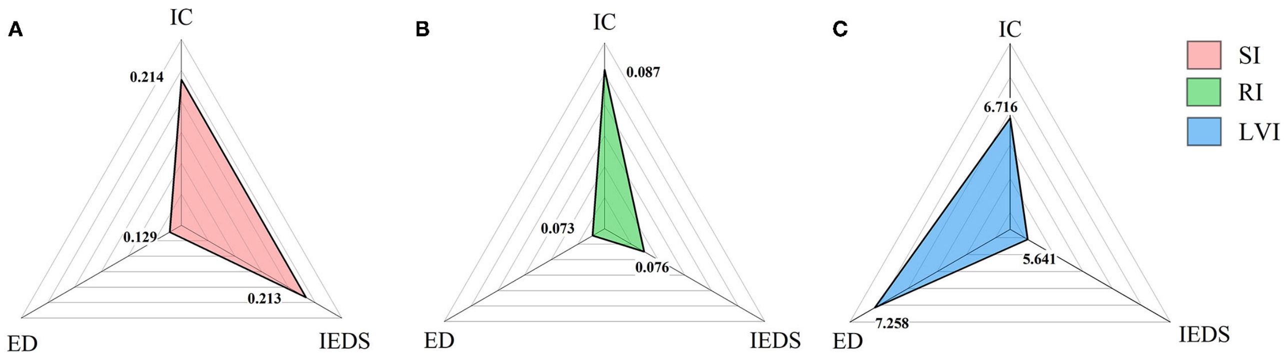

FIGURE 6
(A) Levels of sensitivity index, **(B)** responsiveness index, and **(C)** livelihood vulnerability index. The three corners of each radar plot represent each of the three farmer types.

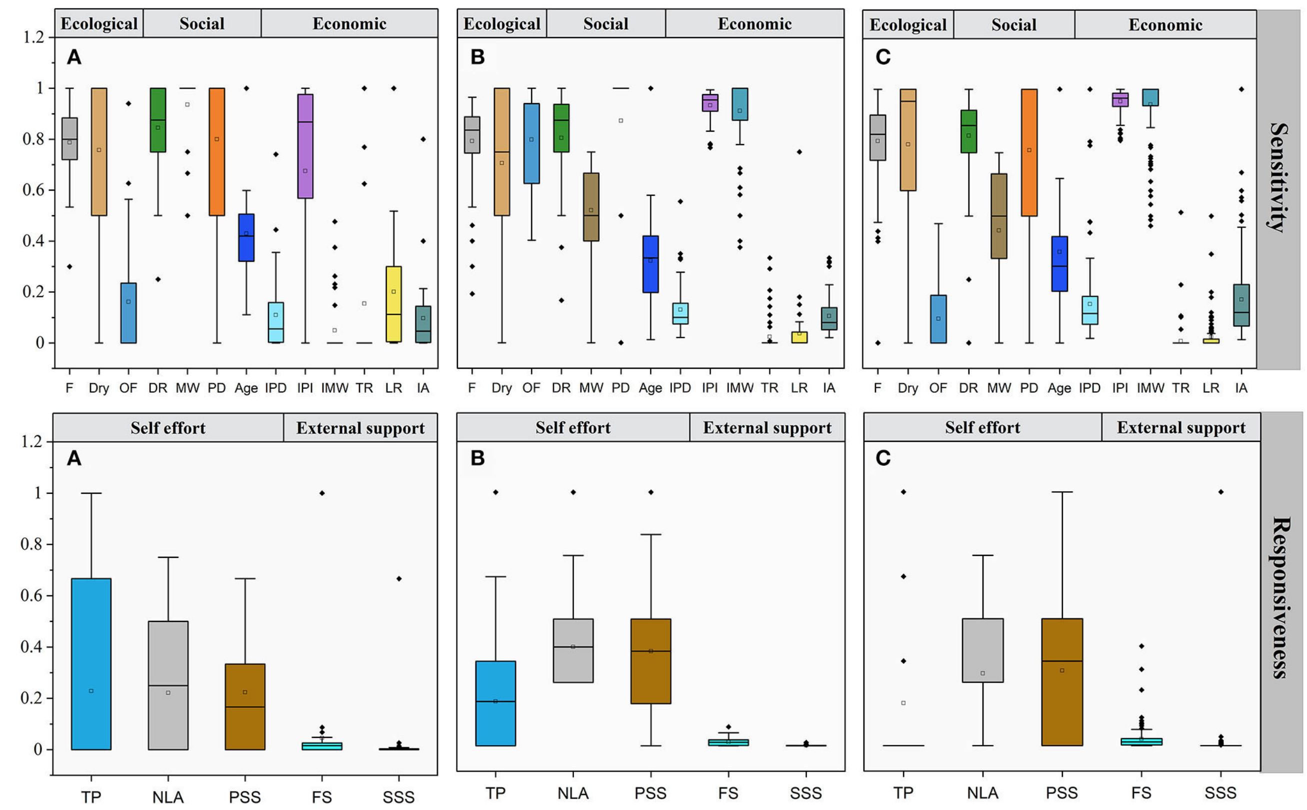

FIGURE 7
Characteristics of farmer livelihood vulnerability with different livelihood types are different: **(A–C)** IC, IEDS, and ED types, respectively. The abbreviations all correspond to the interpretation of the indicators in the indicator system in Table 1.

highest responsiveness of the three (Figure 7B). Thus, the livelihood vulnerability level of this type was the lowest (Figure 6).

iii. **Group ED:** Highly vulnerable-low sensitivity-low responsiveness.

Group ED has the highest income levels, including disposable income per capita and the average income from livelihood activities (Figure 7C). They are mainly located in tourism peripheral area. Dependence on the primary industries and lack of tourism resources resulted in low tourism participation and non-agricultural rates. Arid cropland and unsustainable fertilizer application threatened agroecological security (Figure 7C). Combined with diverse needs and urbanization, this type of farming household is rapidly turning to external livelihoods for support. Peasants in the millennium-old traditional smallholder production system are poorly educated, conservative, and have a single set of skills to earn a living. This leads to a single strategy of working outside the home. The highest vulnerability arose when income support from the local source and policy guarantees were insufficient to compensate for individual capacity deficits. The highest vulnerability always occurs under conditions of relatively high uncertainty rather than low or moderate levels (Fraser and Stringer, 2009). In addition, the highly vulnerable ED group represented the mainstream livelihood model and overall level of vulnerability in the Ziquejie terrace system.

4.3. Differentiation factors of livelihood vulnerability in RTS

The results of the principal component analysis (PCA) showed that PC1 of the sensitivity dimension integrated the indicators including the proportion of migrant workers, the income proportion of the primary industry, and the proportion of migrant workers' income (Figure 9A); PC2 integrated the three main indicators including the proportion of tourism revenue, the local income, and sustenance of livelihood (Figure 9A). We concluded that PC1 represented a system not disturbed by tourism and PC2 represented a system affected by tourism. PC1 of the responsiveness dimension included tourism participation and Subsidies of scenic spots, whereas PC2 included Diversity of livelihood and Level of education (Figure 9B). Therefore, PC1 represented tourism development and PC2 reflected the potential for individual development (Figure 9D).

4.3.1. Spatial differentiation

The PCA results showed that in the sensitivity dimension, the core area was substantially affected by PC2, whereas the peripheral area was mainly restricted to PC1 (Figure 9A). In the responsiveness dimension, the core region was positively correlated with PC1, whereas PC2 positively affected the peripheral area (Figure 9B).

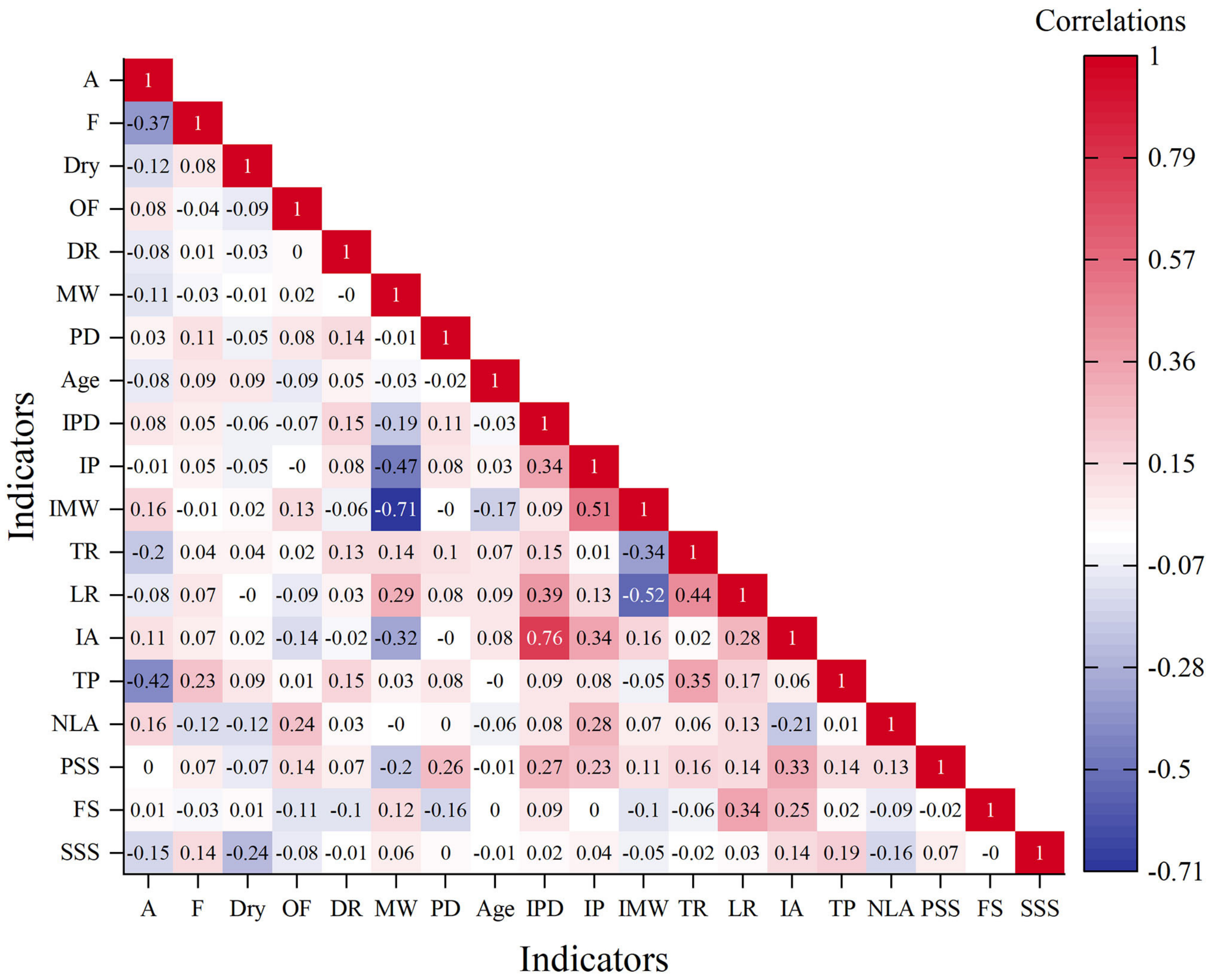

FIGURE 8
Correlation between evaluation indicators.

The Livelihood of the core area showed tourism-led vulnerability. Tourism and local benefit ability (TR, LR), and livelihood replenishment capacity (IA) determine the livelihood sensitivity of farmers in the core area (Figure 9A). They are highly dependent on the imperfect local tourism industry. Threatened agroecological security (Fertilizer application intensity, Drought rate, and Organic farming rate) exacerbated long-term instability in tourism. Limited tourism participation (TP) and scenic subsidies (SSS) contribute to their weak responsiveness to this instability (Figure 9B). Thus, higher tourism revenues and local incomes did not reduce but rather increased vulnerability. Livelihood vulnerability of peripheral is dominated by the flexible strategy of small farmers. The peripheral area lacks a continuous scale terraced landscape to profit from tourism. Even though they are forced to face the risk of low income in the primary sector (IPI) and the instability of outworking (Migrant workers, The proportion of migrant workers' income) (Figure 9C). This still leads to a lower livelihood vulnerability than in the core area. In summary, tourism dependence and flexible farmer strategies drive spatial variation in livelihood vulnerability in the Ziquejie terrace.

4.3.2. Structural differentiation

The principal component analysis (PCA) results showed that PC1 affected the IEDS group, and PC2 significantly affected the IC and ED groups in the sensitivity dimension (Figure 9C). In the responsiveness dimension, PC1 significantly affected the IC group and PC2 affected the IEDS and ED groups (Figure 9D). Farmer strategies drive changes in agricultural and land functions leading to structural differentiation of livelihood vulnerability.

The aging of the workforce has forced the IC group to rely more on the terrace system (Figures 8, 9C). Group IC which was considerably affected by PC2 used an unreasonable fertilization structure to release labor to local tourism and non-agriculture (Figure 7). However, tourism is highly sensitive to the destruction of rice terrace landscape and environment. Fortunately, they can still enjoy some of the benefits of tourism. For example, government subsidies to support farmers involved in development projects. This resulted in a medium level of livelihood vulnerability for the IC group (Figure 6). Group IEDS and the ED group both had exogenous livelihood sources but did not choose to abandon land or farmland. The level of dependence on and benefit from agriculture differs

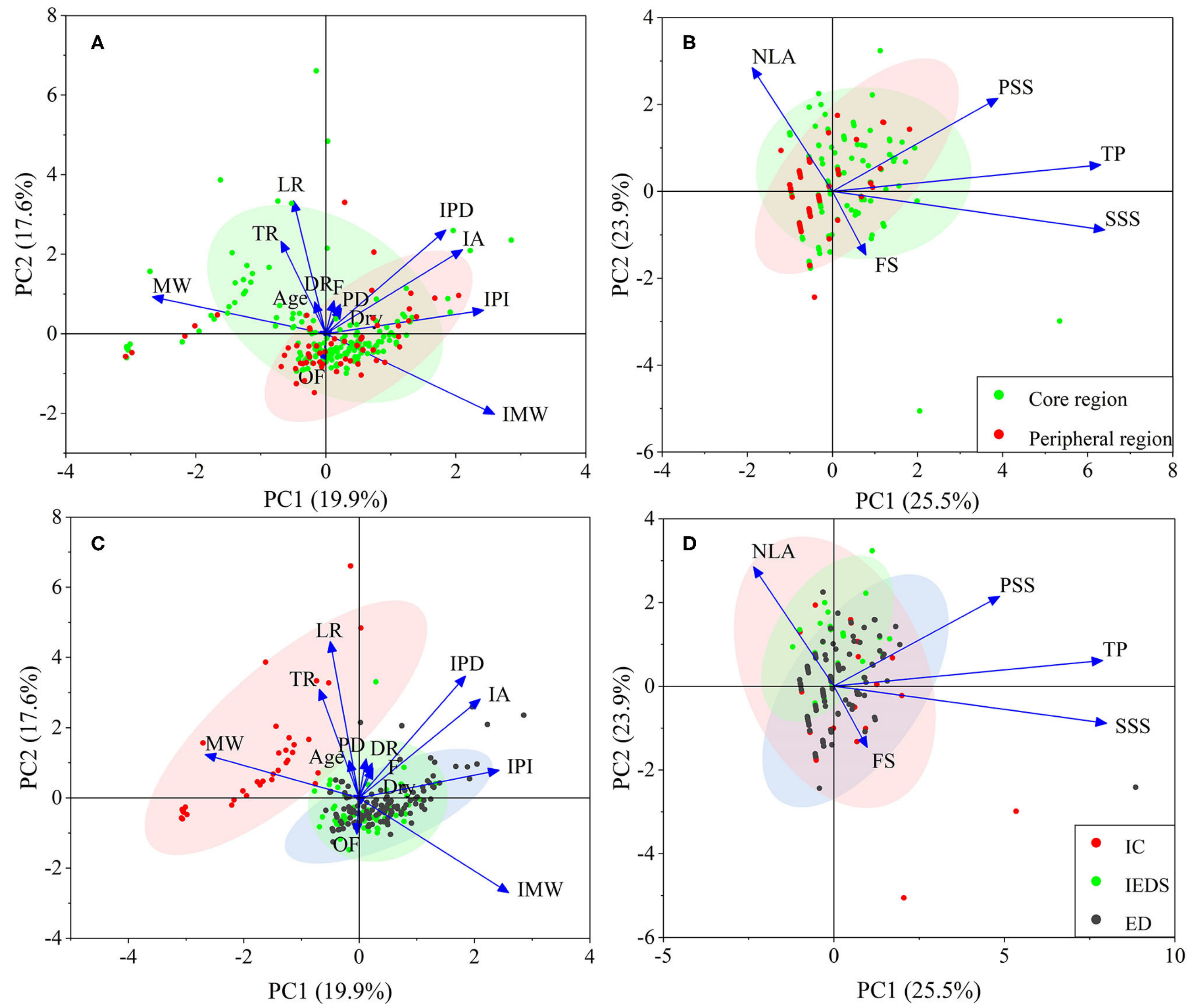

FIGURE 9
PCA plots of farm household livelihood vulnerability under two classifications: **(A, B)** sensitivity and response for spatial classification, respectively; **(C, D)** sensitivity and responsiveness for the three farm household types, respectively.

between the two. They are less sensitive to agroecological risk. Due to the sensitivity of the non-tourism system of the IEDS group (PC1) and the higher capacity of individual development (PC2) (Figure 9). They have the opportunity and ability to enjoy the habitat, food production, and landscape functions of the terraced systems. This also provides farmers with more alternative strategies to circumvent exposure and sensitivity. Group IEDS had the flexibility to share and transform risks between agriculture-non-agriculture. Thus, their livelihood vulnerability was the lowest (Figure 6). The ED group was insensitive to the local tourism system of PC1 but more sensitive to outside sources of livelihood than the IC group. For them, the main function of the rice terrace system was to provide habitat. The TP, LR, and IA indicate that the ED group had limited income from local tourism, non-farm industries, and local livelihood activities (Figure 9). The ED group lacked both the multifunctional support of the rice terrace system and the high individual development capacity. Therefore, their livelihood was the most vulnerable (Figure 6).

In short, farmers have different responsiveness and strategies to the livelihood functions of land altered by tourism development. Structural differentiation of livelihood vulnerability results from this.

5. Discussion

5.1. Key systems for the evolution of livelihood vulnerability

In the above analysis, we identified groups with different livelihood vulnerabilities in the Ziquejie terrace and drivers of mobility between the types. The spatial and structural heterogeneity of livelihood vulnerability in the Ziquejie terrace system suggests that the most vulnerable people are tourism-dependent and exogenous household ED group in the core. Farmers with the lowest livelihood vulnerability (IEDS group) enjoy development project dividends while balancing terraced agriculture. Thus, tourism policy

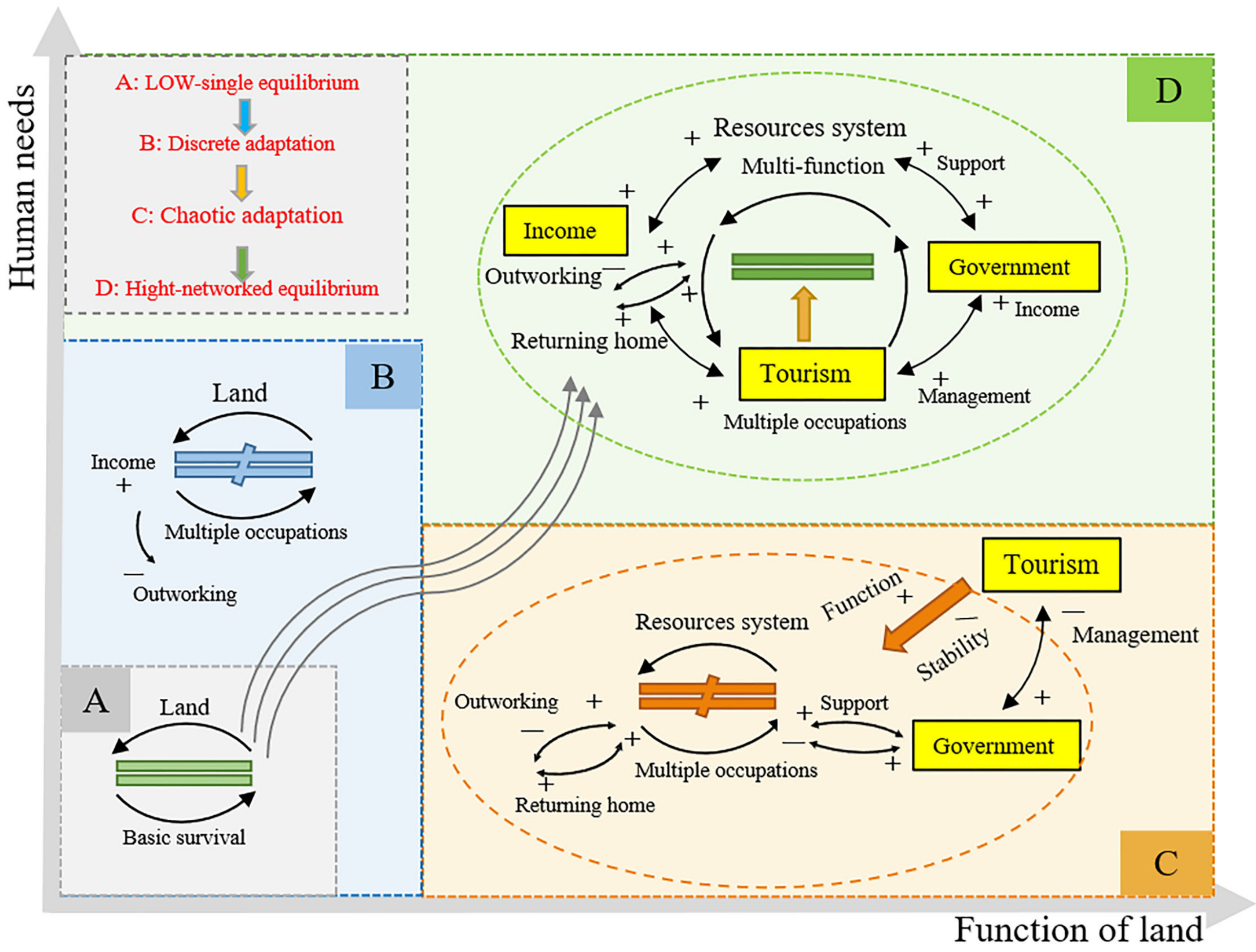

FIGURE 10
Evolutionary cycle of livelihood vulnerability dynamics: **(A–D)** are the four livelihood vulnerability cycles, respectively. The progression of the cycle is accompanied by the fluctuation in land functions on the horizontal axis and human needs on the vertical axis. The disturbance systems represented by tourism and government emerge in stages **(C, D)**. Their feedback relationships with land functions and human needs change.

interventions, agricultural strategies, and land functions together drive the hierarchical differentiation of livelihood vulnerability in RTS. The process of divergence reflects the dynamic trajectory of livelihood vulnerability evolution (Sallu et al., 2010). Thus, we considered the following key systems to explain the dynamic cycles and future trajectories of livelihood vulnerability.

5.1.1. Land function system—Livelihood assets

Land use changes influence the long-term productivity of agroecosystems (Fraser and Stringer, 2009). Traditional rice terrace farmers' livelihoods that depend on agroecosystems have changed. Anthropogenic abandonment in the rice terrace system with severely degraded terraces is limited compared to the national rate of 5% abandonment of cropland (Zhu et al., 2021). Data in Table 2 show that the relatively fragmented terraces still provide important livelihood support in the Ziquejie terrace system. Land provides livelihood functions for different farmers, including habitat, food sources, tourism resources, built capital, and cultural values. Land function systems give farmers public capital for their livelihoods. Spatial location determines what livelihood capital farmers access. This is the base right for farmers to enjoy livelihood dividends from the diverse functions of the land (Wang et al., 2017). Traditional rice terrace farmers' livelihoods that depend on agroecosystems have changed. The opportunity cost of land loss to land users depends on the scarcity of land functions and the dependence on land capital. This critically determines the net livelihood impact of land (Oberlack et al., 2016). The abundant natural capital stock can mitigate livelihood vulnerability caused by social uncertainty and lack of off-farm employment. As a result, farmers who can use land resources can capture more net livelihood gains.

5.1.2. Disturbance system—Livelihood vulnerability environment

Several ancient large rice terrace systems in China are now being developed as tourist attractions (Liu et al., 2018; Zhang et al., 2019). Tourism development of the Ziquejie terrace aims to achieve a win-win situation by exploiting the ecological value of terraces and improving farmers' livelihoods. However, household classification characteristics indicate that tourism weakens the dependence of farmers and tourism-type livelihoods on agriculture in the core area, but strengthens the dependence on ecological and landscape resources. It promoted the transformation rather than the disappearance of transformed farmers' livelihood stressors. Because this disturbance increases political and economic uncertainty (Fraser and Stringer, 2009). Thus, the trade-off with agriculture affects the attributes of tourism on the increase or decrease of farmers' livelihood vulnerability. Elucidating the negative impact of tourism on the evolution of livelihood vulnerability does not negate its role in raising farmers' income levels. This precisely emphasizes that tourism complement rather than replaces the livelihoods of terraced agricultural systems (Petrosillo et al., 2006).

5.1.3. Demand system—Livelihood strategy

Human needs as reflected by livelihood strategy relate to the connectivity, diversity, and stability of physical and socioeconomic networks (Dressler et al., 2019). The importance of objective socio-economic and policy factors in creating fragile rural economies and land-use systems, even leading to collapse, has been well-documented (Fraser, 2003). But this is only a macro context. Farmers are the actual recipients of benefits from the land and terraced ecosystem functions and services. This compensated for the inadequacy in explaining livelihood vulnerability in terms of land and environmental systems alone. Farmers in the core area enjoy the resources to participate in multifunctional development projects on the land (Figure 5). Strategies to engage in tourism policy-driven non-agricultural or outworking emerged from this. Diverse and flexible livelihood strategies are important drivers of the evolution of terraced farmers' livelihood vulnerability.

5.2. Dynamic cycles of livelihood vulnerability

In this study, we captured the dynamic trajectories and cycles of livelihood vulnerability in the RTS in terms of spatial and structural characteristics. Based on the key systems discussed above, we argue that a model can be developed for the evolution of livelihood vulnerability in a coupled human-environment system under disturbances (Figure 10). The operation of the model would rely on the emergence, development, and interrelationships of the three key systems. The main aspect of the model would be the dynamics of the relationship between the transformation of the functional value of the land and the development of human needs during disturbances. Disturbance as an intervention reinforces the game of human–land relationships in the evolution of simple vulnerability. One of the main reasons for this cyclicality is that strategies and actions taken to adapt may exacerbate, rather than mitigate, the present vulnerability. In addition, short-term strategies may erode the resources needed to cope with future stressors, thereby increasing the levels of uncertainty. The emergence and specific characteristics of the evolutionary cycle are as follows.

A. **Low-single equilibrium stage:** This is a phase in which both human demand and land values are low. The sole function of the land is to provide subsistence to meet human food and housing needs. Both maintain an equilibrium between supply and demand in a double-chain-type circuit (Figure 10). Farming is the only livelihood strategy for farmers.
B. **Discrete adaptation stage:** Along with social development, human needs level increases. Government promotion of land value diversification is an objective requirement to meet the needs of terraced farmers. Off-farm income sources remove some people from marginal agriculture (Job and Paesler, 2013). Increased social mobility is accompanied by an increase in the accumulation of unnatural capital in a system (Figure 10). However, policy forces drive social thresholds to achieve state transitions faster than incremental biophysical environmental boundary crossings (Fanning et al., 2021). The lag in the transformation of land values has led to negative consequences of the transformation of livelihood strategies. This phase is characterized by a discrete disequilibrium in which human needs are not met by land.
C. **Chaotic adaptation stage:** Land use depends on environmental conditions, but is also derived from socio-economic and policy forces, over which farmers have little control. Thus, ecotourism development is used as an adaptive action by local farmers after the previous phase (Hultman and Säwe, 2016; Jia et al., 2021). The local government or the adaptive management organization guides the capital of tourism injection and exploits the value of land diversification. This promoted new behaviors and expectations of previously constrained or marginal households. Based on the analysis of the results, the core area and IC group farmers were considered victims of the chaotic phase. Insufficient policy power leads to a lag in the transformation of land value. Meanwhile, the transformation of farmers' livelihood strategies lagged behind the policy drivers. Closed-loop pathways could not be formed between farmers' livelihoods, land values, and management systems. Essentially, a group is pushed to a threshold, resulting in the loss of the original source of security and certainty (Carr, 2019). Thus, imperfect tourism management, limited farmer strategies, and still lagging land values have led to a chaotic state at this stage (Figure 10).
D. **Highly networked equilibrium stage:** This stage achieves a high level of positive feedback loops in multiple pathways. Farmers who pass through the chaos stage become aware of the role of subjectivity in ensuring livelihood security and reducing vulnerability (Carr, 2020). Farmers with resources can become overly dependent and fall into the "resource curse." The game between people and land was more pronounced in the core area. This suggests that the disturbing property of tourism on livelihood vulnerability is bidirectional. Increasing the support of terracing systems for livelihoods can induce the most vulnerable ED farmers to accelerate their entry into this equilibrium phase. Resource acquisition, value transformation, and human-land synergy are particularly important in this process. At this stage, the multiloop equilibrium is the result of fully positive feedback between the farmer as the subject, the political system, and the disturbance system represented by tourism (Figure 10). The IEDS farmers with the lowest livelihood vulnerability are representative of this stage. Farmers' natural and unnatural capital is steadily accumulating. They achieved sustainable livelihoods in the terraced system based on reduced dependence, increased flexibility, and actual profitability.

Three key systems (land values, human needs, and disturbances) drive the evolution of livelihood vulnerability from states A to D (Figure 10). The level of vulnerability also shifts from a stable, medium level to a high level of disturbance, followed by a decrease to a stable, low level. This process has led to the spatial differentiation of livelihood vulnerability and the stratification of farm households in rice terrace systems.

6. Conclusions

Our study highlights the importance of disaggregated household analysis for exploring livelihood vulnerability dynamics. First, the livelihood vulnerability of farmers in the core area as a terraced resource-rich area is underestimated. The implementation of development projects has provided them with development opportunities. They are perceived to benefit while the real livelihood vulnerability of some farmers is misunderstood. They incur opportunity costs when they transition. The short-term benefits of imperfect tourism do not compensate for the long-term loss of resources. For rice terrace systems, terraced and non-terraced agriculture is the basic guarantee of all farmers' livelihood. This undoubtedly emphasizes that terraced agriculture is the fundamental guarantee rather than the only option for farmers' livelihoods to remain stable in rice terrace systems. Tourism development should do more to ensure the sustainability of terrace landscape resources and rice agriculture. The government and tourism management should effectively utilize the ecological and economic value of the additional functions of the land. This requires a clearer mechanism to coordinate the relationship between the government, the scenic sector, the terraced-land system, and farmers' livelihoods. In addition, the current response of farmers in terraced systems to changes in their livelihood environment is still very passive. Policy and tourism management should pay more attention to the heterogeneity of farmers' unit participation in land resource use and development projects. They should provide differentiated transformation strategies for farmers with different levels of vulnerability. For example, the government should create strong incentives to promote the integration of agriculture and other industries; Effective employment and risk protection measures should be maximized and increased; Relevant employment training should be adopted as necessary. The above measures can facilitate the farmers to play their main role in the rice terrace system. This is the key for livelihood vulnerability to move from the chaotic adaptation phase to the high-level network equilibrium phase.

Farmers' livelihood vulnerability is related to the actual and stable contribution of RTS functions and services to farmers' economic wellbeing. Thus, finding the dynamics of livelihood vulnerability evolution in rice terrace systems for sustainable development is the ultimate goal of this study. Our proposed evolution model differs from the collapse and reorganization process that the state of the system inevitably undergoes in resilience theory. The coordination of inter-system relationships promotes the evolution of livelihood vulnerability stages. Livelihood stabilization to achieve internal self-circulation is a breakthrough to resolve the current human-land conflict in the RTS. Our study will help to provide new scientific references for the conservation development of many agro-cultural heritage systems and traditional smallholder systems.

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 authors.

Author contributions

CD: investigation and writing—original draft. SW: investigation, formal analysis, writing—original draft, visualization, data curation, and writing—review and editing. YL: investigation and writing—review and editing. ZL: supervision. GZ and CL: investigation. WL: investigation and software. All authors contributed to the article and approved the submitted version.

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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

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