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Research on factors affecting sustainable development in ecologically fragile areas based on a social-ecological system framework

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Abstract

Since modern rural development results from a complex interaction between various exogenous forces, the sustainable development of rural communities in ecologically fragile areas is inherently a systemic endeavor. This study, guided by the social-ecological system theory, examines the impact of social, economic, political, natural, and other external factors on the sustainable development of rural communities in these areas. The goal is to gain a deeper understanding of the underlying causes of delayed development in these communities. The results are as follows: First, labor outflow, ecological fragility, and informal institutions significantly hinder the sustainable development of rural communities, while regional economic development demonstrates a strong positive relationship with the sustainability of rural communities. Second, regional economic development primarily influences the sustainability of communities through its impact on locational conditions. Communities closer to the county and town experience a more pronounced positive effect from regional economic development. Thirdly, informal institutions inhibit the sustainable development of rural communities by obstructing the land rights reform process.

Finally, for small-scale communities, the inhibitory effect of ecological fragility and the facilitating effects of regional economic development are more substantial, while labor outflow and informal institutions exert a pronounced inhibitory effect primarily on large-scale communities. For low-poverty communities, labor outflow exerts a more significant inhibitory effect on community sustainability. In contrast, for high-poverty communities, the regional economic development contributes more significantly to sustainability, while ecological fragility and informal institutions have a stronger inhibitory effect.
Keyword: Sustainable Development; Rural Communities; Ecologically Fragile areas; social-ecological system.

1 Introduction

Rural decline has become a contentious issue in the international community due to the acceleration of urbanization and industrialization[[1]]. Rural decline is characterized by large-scale population loss and challenges, including shrinking markets, economic recession, social degradation induced by labor shortages, and the gradual erosion of endogenous development capacity[[2]]. However, unlike the self-sufficiency model of agricultural societies, contemporary rural development results from a complex interplay of multiple exogenous factors, including demographic, social, community, and environmental factors, which are often interdependent[[3]]. Despite the increased risk posed by the complexity and variability of the external environment, some villages have prospered through their interaction with these external factors, while others have faced extinction[[4]]. Understanding the causes of these outcomes has become a significant area of study for researchers.

Overall, sustainable rural development is shaped by multiple factors, including the natural environment, policy and institutional frameworks, and urbanization trends[[5]]. Since the Industrial Revolution, the urban sector has become the dominant force influencing rural development[[6]]. Through the process of resource concentration, cities have extensively exploited rural resources, including the disproportionate land expropriation for urban expansion[[7]], the excessive exploitation of rural natural resources[[8],[9]], and the migration of many rural inhabitants to cities[[10]]. Reassuringly, an increasing number of policies promoting sustainable rural development and rural revitalization have been formulated in Europe, China, and other countries since the 1990s[[11],[12]]. Much of the research on rural development has

focused on the role of policy, such as urban preference policies[[13]], fiscal policy[[14]], and the household registration policy[[15]]. Furthermore, several scholars argue that the outward migration of rural populations is a key factor contributing to the decline of rural communities and local economies[[16]-[18]].

However, current research on urban-rural relations and rural development policies remains somewhat contentious. For instance, as urban economies expand, their benefits gradually diffuse into rural areas through positive externalities, such as improved rural social welfare and infrastructure[[19]], as well as through transformations in rural livelihoods and food systems[[20]]. Conversely, Li et al. (2013) suggest that a top-down policy approach may constrain rural autonomy, preventing rural areas from effectively responding to macro-level development strategies[[21]]. In contrast, bottom-up development models—such as social innovation—can stimulate local potential and promote sustainable rural development[[22]].

In the 1990s, the relationship between human activity and the environment gathered significant societal attention. International ecology introduced the concept of "fragility" into research fields such as geographical environments and spatial studies. Ecologically fragile regions, often located at the edges of ecosystems or within transitional zones where multiple ecological types converge[[23]-[26]], face particularly severe challenges. The fragility of these ecosystems[[27],[28]], the risks to livelihoods[[29],[30]], and social instability[[31]-[33]] are all more pronounced in such areas. Consequently, their capacity for sustainable rural development lags behind that of more stable regions.

It is evident that the issue of sustainable rural development in ecologically fragile regions is more complex than in other areas, as it necessitates further examination of the influence of factors such as urban components and policy frameworks on rural development. Furthermore, few studies have integrated these elements into a unified analytical framework to examine how each factor influences the sustainable development of rural communities, considering the combined roles of these components. Eventually, the research methodologies employed in the existing literature tend to be quite similar, primarily relying on case analysis, indicator evaluation, and other methods to analyze sustainable rural development in ecologically fragile areas. However, there is a need to incorporate more empirical research into this field to strengthen the scientific nature of these studies.

This study employs the social-ecological system (SES) framework as a guiding theory to analyze the factors affecting rural

communities in ecologically fragile regions, addressing these gaps. To highlight internal variations within communities, this study utilizes data from rural community surveys. It applies OLS regression models, Tobit models, group regression, and mechanism analysis to examine the impact of various factors on the sustainable development of these communities. The contributions of this study are twofold: From a theoretical perspective, using a socio-ecological systems research approach, we identified four key components—labor force, ecology, institutions, and economics—that influence sustainable development in rural communities located in environmentally fragile regions. In an effort to establish an innovative theoretical paradigm for rural development, these components were integrated into a unified conceptual framework. From a research methods perspective, the study employs a range of empirical approaches to investigate the impact of factors such as labor outflow, ecological fragility, institutional environment, and economic development on the sustainable development of rural communities in these regions. This approach enhances the explanatory power of the factors contributing to the lagging development of rural communities in ecologically fragile areas.

2 Theoretical analysis

The SES framework is a comprehensive analytical model composed of multiple levels of variables. It includes six core components: resource system (RS), resource units (RU), governance system (GS), and users (U), all of which interact with the behavioral interactions (I) and outcomes (O) of individuals and groups in a given action situation. Additionally, the interactions and outcomes among these variables are influenced by two subsystems representing the overall environment: the social, economic, and political context (S) and the relevant ecosystem factors (ECO) (Figure 1). The impact of "external variables" on the strategy process, such as the effects of drought on resources or floods on public infrastructure in the ECO system, is significant. These six-level core subsystems (RS, GS, RU, U, I, and O) within the SES framework provide a basic structure that provides a foundation for more detailed representations of how the strategy process is implemented[[34]]. The effects on the 1–6 basic structure are dynamic, meaning that the sustainability trajectory of the entire SES will evolve accordingly. External variables such as ecological, social, and economic factors are inherently unpredictable and subject to constant change[[35]]. Within the robustness framework, the social, economic, and political (S) system encompasses social development, demographic trends, political stability, government resource policies, market incentives, and

media organizations. In contrast, the ECO system encompasses climate, pollution, earthquakes, and landslides[[36]]. Further judgment is required regarding external variables: first, whether there are thresholds for these variables; second, their historical regularity to predict how the system dynamics will respond to future external shocks; and third, the attributes of these variables, such as whether they are "slow" or "fast" variables and whether they are controllable (land-use policy) or uncontrollable (climate)[[37]].

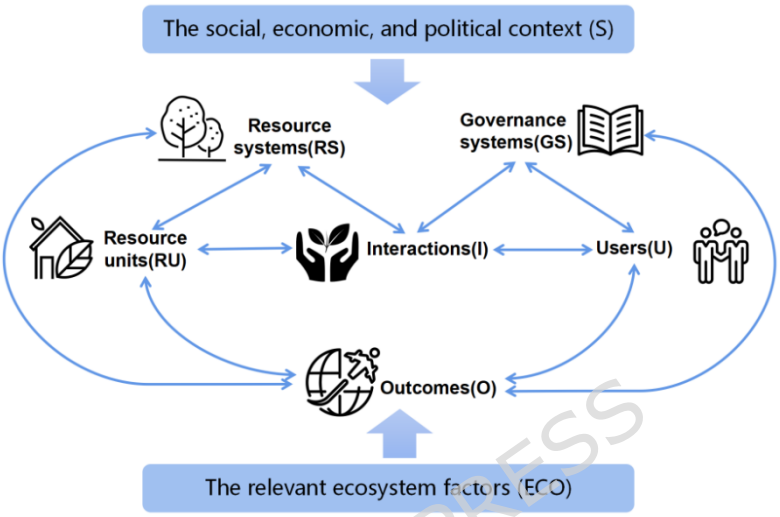

Figure 1. The core subsystems in a framework for analyzing the SES.

Rural communities represent typical socio-ecological systems comprising both natural resources, such as land and rivers, and resource users and stakeholders, including community members, governmental decision-making bodies, and social organizations[[38]]. According to the SES framework, rural communities are influenced by the social, economic, and political (S) system and the ECO system. Labor migration is considered an exogenous shock in this framework, given the substantial outflow of rural populations[[39]]. Therefore, this study considers labor, institutional, economic, and ecological factors as second-level variables under the social, economic, and political institutions (S) and the ECO system, which affect the sustainable development of rural communities in ecologically fragile areas (Figure 2).

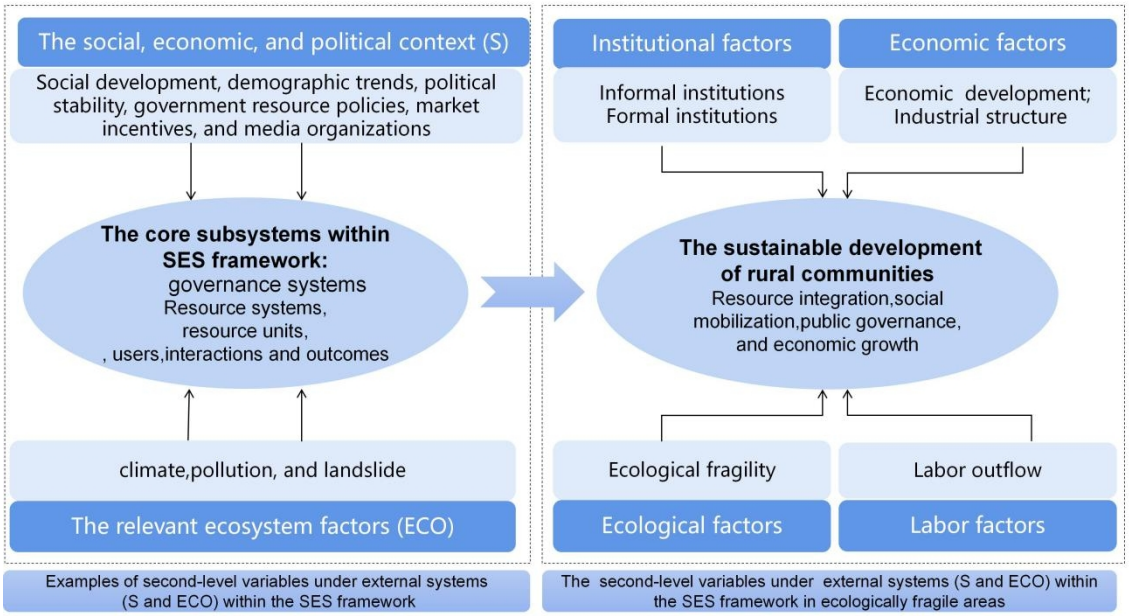

Figure 2. The factors affecting the sustainable development of rural communities based on the SES framework.

(1) Ecological factors. Natural resources are a crucial element in the sustainable development of rural communities, as the livelihoods and production of rural residents are heavily dependent on natural capital[[40]]. However, a symbiotic relationship exists between natural resources and their environment; the health of the ecosystem affects the quantity and quality of resources, as well as how humans utilize and develop them. Ecosystems, with poor organic matter, biota, topography, and climate stability, are highly vulnerable. This makes the capacity of natural resources—such as arable land, forest land, and grassland—to absorb and store energy relatively low. The quantity and quality of natural resources are subject to significant constraints. Furthermore, the poor quality and dispersion of land resources severely limit the basic livelihoods of residents and community development[[41]].

(2) Institutional factors. Social institutions are key drivers of socio-economic development[[42]]. Within the SES framework, policy institutions can create new contexts for action or participation, thereby intervening in and influencing governance systems or actors' behaviors[[43]]. Formal institutions established by government authorities operate through enforceable regulatory mechanisms, whereas informal institutions function through individually or socially embedded constraints. To some extent, however, the existence of informal institutions can also serve as a critical force driving development[[44]]. In the context of rural sustainable development, rural communities can achieve collaborative governance and participatory decision-making through specific institutional arrangements. Formal institutions provide a stable

social order for the sustainable development of rural communities and represent the concrete embodiment of national policies at the local level. Conversely, informal institutions shape the morality, values, and social interactions of villagers, influencing cooperation, willingness, and trust among members. This, in turn, affects transaction costs and member cooperation[[45],[46]].

Beyond their direct effects, both formal and informal institutions exert indirect influences on the SES through the structure of property rights[[47]]. Particularly in China, these institutions further shape rural development by influencing land property rights[[48]]. Theoretically, well-defined property rights ensure the efficient flow of resources across sectors, allowing markets to allocate resources optimally[[49]]. Moreover, property rights play a vital role in maintaining social stability and providing social security[[50],[51]]. An effective property rights framework is also essential for addressing issues related to power dynamics and the distribution of benefits within communities[[45]]. In rural China, collective ownership of land and means of production encompasses multiple attributes, including collective and community property rights. These property rights not only guarantee residents' basic rights to land and residential plots[[52]] but also provide a legal foundation for accessing public benefits such as community healthcare and pension programs[[53],[54]]. In recent years, to strengthen farmers' property rights and enhance community governance, the government has promoted property rights reform through a series of policy initiatives[[55]-[57]]. These reforms aim to regulate the scope, methods, and objectives of property rights changes, which, in turn, can have a positive influence on rural communities.

However, unlike private property rights, the establishment of collective land ownership rights presents exceptional challenges[[58]]. Rural communities often require land readjustments to accommodate changes in household size. Factors such as unstable land tenure, the absence of formal registration procedures, and ambiguous criteria for defining ownership boundaries can give rise to numerous land disputes. If farmers participate voluntarily and proactively, the process of rural land reform and rights confirmation can be considerably streamlined[[59]]. Regarding farmers' behavioral intentions, Mcnicoll and North (1991) emphasize that ideology significantly shapes actors' cognition and subjective understanding[[60]]. In rural China, informal institutions, including local knowledge, shared values, and normative constraints, play crucial roles in shaping villagers' participation in community life[[61]]. Evidently, informal institutions influence rural communities by affecting members' engagement in land property rights reform

processes.

(3) Economic factors. Within the SES framework, macroeconomic variables drive rural socio-economic development by optimizing rural resource system[[62]]. Particularly with the advancement of regional economic integration, economic development in rural areas is primarily driven by factors such as new technologies, market competitiveness, and the growth of the non-farm economy[[63]]. In general, new technologies and market competitiveness are linked to the level of regional economic development; the higher the level of economic development, the more investments are made in rural technology, capital, and other high-level factors by governments, enterprises, and external factors. As a result, rural communities are better positioned to allocate resources efficiently under market-driven conditions[[64]]. The influence of manufacturing and services on rural areas stems from intersectoral spillovers, and the expansion of the non-agricultural sector can drive industry upgrades, thereby accelerating the transformation of traditional agriculture into multifunctional agriculture[[65],[66]].

However, the geographical and spatial location is also a key factor influencing the development of rural communities. The closer a rural community is to a city, the stronger the symbiotic relationship between them, fostering economic radiative effects, such as factor mobility, spatial planning, and industrial layout optimization. These dynamics, in turn, promote the upgrading and transformation of rural industries[[67]]. Furthermore, research indicates that townships—the smallest units of urban-rural integration—play a critical transitional role in this process, serving as hubs for factor aggregation and rural economic growth[[68]]. Therefore, this study investigates the influence of proximity to cities and townships on the sustainable development of rural communities.

(4) Labor factors. Neoclassical economic theory posits that a significant portion of "surplus labor" from the agricultural sector will naturally shift to the urban industrial sector as wage gaps between the two sectors equalize[[69]]. However, part of the labor outflow from rural areas can be attributed to "imaginary surpluses" caused by poverty and socio-economic lag rather than a true surplus resulting from agricultural modernization and increased labor productivity[[70]]. Consequently, younger, relatively better-educated male laborers are more inclined to migrate from rural areas in ecologically fragile areas to urban centers. This exodus of skilled labor leads to population decline and demographic imbalances in rural areas, leaving behind the older adults, the vulnerable, women, and children[[71]]. The outflow of labor not only exacerbates issues

such as labor shortages, rising labor costs, and declining human capital, but also negatively affects the sustainable development of rural areas. This is because it weakens public leadership in villages, erodes accumulated social capital, dilutes villagers' sense of belonging, and reduces farmers' dependence on agricultural resources[**Error! Reference source not found.**].

3 Research methods and Data sources

3.1 Research methods

A standard approach for examining the impact of explanatory variables (influencing factors) on dependent variables is through the use of least squares regression. This study follows this method to analyze the relationships, constructing the model as follows:

$$y = \alpha_0 + X_i\beta_1 + Controls\beta_2 + City_j + \mu_i \quad (1)$$

Where y represents the dependent variable, the level of sustainable development of rural communities; X includes the core explanatory variables, namely ecological fragility (*Eco*), regional industrial structure (*Industry*), regional economic development (*Pergdp*), formal institutions (*Formal*), informal institutions (*Informal*), and labor outflow (*Labor*). Additionally, control variables include geographic environment (*Altitude*), number of farm households (*Family*), per capita income (*Income*), and regional dummy variables *(City)* representing different cities.

3.2 Data sources

The data used in this study consists of both macro-level statistics and micro-level research data. Macro-level data, such as regional economic indicators, industrial structure, and formal institutions, are primarily sourced from the Guizhou Statistical Yearbook. Micro-level data, including information on ecological fragility, labor outflow, informal institutions, and geographic environment, were collected through field research conducted by the research team. The field research consists of three main stages:

The preliminary preparation stage involved designing statistical forms and interview outlines. Drawing upon existing literature and considering the developmental characteristics of rural communities in ecologically fragile regions, the study designed two instruments: the Basic Statistical Form for Rural Community Development and the Interview Outline. The Basic Statistical Form was primarily used to collect objective factual data on the development of sampled communities in 2021. Completed by relevant community staff, it covered fundamental aspects such as community demographics,

resource utilization, economic conditions, and social development indicators. It included information on population, labor force, aging demographics, number of party members, geographical location, natural resources such as total land area, arable land, forest land, and water bodies, as well as community assets like operational construction land and idle properties. Socio-economic development indicators, including industrial composition, per capita net income of farmers, asset investment, and community economic revenue, were also recorded, along with data on community governance, educational attainment of community leaders, and public infrastructure.

In June 2021, a preliminary survey was conducted in Guizhou Province, covering 20 rural communities across Panzhou, Zhenyuan, and Shiqian counties (cities). Based on feedback from this initial survey, the statistical tables were refined and revised through consultations with domain experts and project team members, ultimately producing the finalized versions. The expert group consisted of six specialists, including researchers from the Guizhou Academy of Agricultural Sciences, government officials from agricultural departments, and professors specializing in population, resource, and environmental economics.

From July to August 2021, extensive field research was conducted across rural communities in Guizhou Province, utilizing a combination of fixed-point random sampling and snowball sampling. Fixed-point random sampling ensured the scientific selection of samples, while snowball sampling enhanced the diversity and inclusiveness of research participants. Given the challenges of obtaining data from rural communities, support was secured from local agricultural departments in each county, city, or district. One to two representative counties were selected from each prefecture-level city or autonomous prefecture in Guizhou Province, excluding the provincial capital, Guiyang. Within each selected county or district, two to three representative townships were chosen, from which three to four sample communities were randomly selected for field investigation. This process yielded first-hand community data through in-depth and semi-structured interviews, supplemented by the completion of the Statistical Form on Basic Rural Community Development. With assistance from township officials, contact details of village cadres in other administrative villages within the same township were obtained, and these cadres completed the Statistical Form on Basic Rural Collective Economic Development via telephone or e-mail. The sample size was determined with reference to existing studies. For example, Li and Yao (2020) selected 246 administrative villages in Shaanxi Province[[72]], while

Zhou and Kang(2019) selected 271 administrative villages in Liaoning Province[[74]]. In the present study, a total of 240 statistical forms were distributed. After excluding incomplete or invalid responses, 227 valid questionnaires were obtained, yielding a response rate of 88.89%. Accordingly, the sample size in this study is adequately representative of the overall situation. Regarding sample distribution, the data encompass rural communities across Guizhou Province, including those with strong, moderate, and weak socio-economic development, thereby demonstrating robust representativeness.

3.3 Measurement of variables

3.3.1 Level of sustainable development of rural communities

Based on the United Nations Sustainable Development Goals (SDGs), sustainable development in rural communities is not only about promoting the sustainability of the natural ecosystem but also ensuring that future generations have access to the same or better conditions than present generations to meet their natural, social, economic, and other needs[[75]]. Several studies have developed rural sustainable development indicator systems based on the framework of the SDGs to comprehensively analyze the local characteristics of rural systems and rural revitalization strategies[[76],[77]]. However, with the emergence of rural autonomous development models, recent research suggests that assessing rural areas through a resilience perspective can proactively identify both external pressures and internal changes affecting rural systems. This approach enhances understanding of the resource configurations and functional mechanisms of these systems[[78]]. Rural resilience theory, derived from ecosystem frameworks, emphasizes the capacity of communities to absorb disturbances while maintaining essential functions[[79]]. Wilson et al. (2018) argue that rural system resilience is inversely related to fragility; continuous improvement in resilience signifies a gradual reduction in community fragility[[80]]. Rural system resilience is closely linked to economic, social, cultural, and political dimensions. Drawing on established resilience assessment frameworks, this study selects four dimensions to evaluate the sustainable development of rural communities. First, economic growth[**Error! Reference source not found.**] plays a foundational role in sustainable rural development. Economic diversification and sustainability enable rural communities to pursue independent development, allowing collective members to broaden their livelihood options and increase income levels[[4]]. Second, social mobilization constitutes a critical element in building community resilience[[1]]. Expanding social networks encourages participation

from groups such as returning entrepreneurs, village committees, and rural residents in community development. Such participation strengthens social relationships, enhances social capital, and facilitates access to information and other resources. Third, resource integration[[81]] is essential, as rural communities are complex systems composed of natural endowments, geographical conditions, economic foundations, human capital, and cultural traditions. The primary challenge in advancing sustainable rural social development lies in correcting resource allocation distortions. This requires optimizing the structure and functionality of rural communities by coordinating and integrating the management of both tangible and intangible assets[[83]]. Fourth, public governance[[84]] addresses the distribution of interests and power among stakeholders, including community members, local committees, government agencies, and external markets. The governance process involves coordinating resource elements and resolving conflicts among diverse actors through policy interventions, governance mechanisms, and institutional frameworks. Effective public governance enhances the sustainability and efficiency of collective community action[[85]].

The relevant level-3 indicators are developed based on the existing literature (Table 1). According to research by Chen (2020)[[86]], this study chose the mean value of the entropy value and the analytical hierarchical process (AHP) to determine the weights of various indicators.

Table 1 Evaluation system for sustainable development of rural communities

First Layer	Second Layer	Third Layer	Index Content	Attribute
Sustainable development of rural communities	Resource integration C1	Cultivated land C11	The area of cultivated land owned by each member includes paddy fields, water, and dry land etc.	+
		Woodland C12	Area of woodland owned by each member, including forests, mountains, wasteland, orchards, etc.	+
		Water resource C13	Area of water resource owned by each member, including lakes, rivers, etc.	+
		Operating construction land C14	Mainly community-owned collective operating construction land.	+
		House C15	Unused village primary schools, abandoned rural residences, and other facilities are available to the community.	+
		Government funding C16	Total funds spent by the government on community development.	+
		Community funding C17	Cumulative value of community account funds for the year.	+
	Social mobilization C2	Professionalism of community leaders C21	The number of professional trainings and learning received by community leaders during the year.	+
		The educational level of community leaders C22	The proportion of community leaders and managers with a high school diploma or higher level of education.	+
		Community leadership appraisal institutions C23	Whether the effectiveness of community development is included in the assessment of leaders and managers (1 = yes, 0 = no).	+
		Community action organization C24	Whether community action organizations are formed (1 = yes, 0 = no).	+
		Level of government sector participation C25	The proportion of political party members in the community.	+
	Public governance C3	Leadership incentivesC31	Whether leadership compensation incentives exist (1 = yes, 0 = no).	+
		The benefit-sharing mechanism for members C32	Whether a mechanism for distributing the benefits of membership is present (1 = yes, 0 = no).	+
		Public utilities development C33	During the year, expenditure is made on public utilities, including environmental protection, infrastructure, and rural development.	+

		Democratic participation C34	The number of meetings related to community development attended by members during the year.	+
	Economic growth C4	Capital growth C41	Total community assets for the year.	+
		Income growth C42	The combined value of operating and investment incomes for the year.	+
		Profitability C43	Operating income is the total amount for the year.	+
		Bonus C44	A bonus for each member for the year.	+

Using a linear weighting method to calculate comprehensive scores, this study evaluates the sustainable development level of rural communities and the performance of each subsystem in the sampled region, as presented in Table 2. The average sustainable development score for rural communities in the sample is 15.35, with a maximum of 45.06 and a minimum of 1.20, indicating a difference of 43.86 and a marked imbalance in development levels. From a subsystem perspective, the public governance (C3) and social mobilization (C2) dimensions perform relatively well, while the economic growth (C4) dimension exhibits the weakest performance. These findings are consistent with those of Yang et al. (2021)[[15]]. Compared with other regions in China, rural community development in Guizhou remains at a relatively lagging stage, characterized by significant risks and uncertainties in sustainable livelihoods, and economic efficiency[[87]]. Village resilience represents a systemic concept that depends on the synergistic interactions among social, economic, and environmental systems[[88]]. This is consistent with the findings of Li et al. (2022)[[89]], which indicate that communities with higher comprehensive resilience indicators are better able to withstand stress, adapt to change, and undergo learning-driven transformation. Conversely, some communities exhibit weak resilience because they perform poorly on specific dimensions of resilience.

Table2 Development level of the sustainable development and subsystems values.

	C1	C2	C3	C4	Composite index
Average value	2.30	5.59	6.48	0.98	15.35
Median	1.82	6.45	6.99	0.21	14.81
Crest value	12.94	11.26	19.54	20.39	45.06
Least value	0.00	0.71	0.00	0.00	1.20

3.3.2 Measurement of other variables

The selection of six factors from ecology, economy, society, and labor force was based on theoretical research and practical development data. These factors include ecological fragility (*Eco*), regional industrial structure (*Industry*), regional economic development (*Pergdp*), formal institutions (*Formal*), informal institutions (*Informal*), and labor outflow (*Labor*).

Ecological fragility (*Eco*). Timmerman (1981) defined fragility as the degree to which a system experiences adverse effects or damage in response to external disturbances[[90]]. Fragility is generally understood as a function of three components: susceptibility to exposure, sensitivity to stressors, and the system's capacity for recovery. Turner et al. (2003) argued that ecological fragility depends not only on the degree of exposure to hazards (disturbances and stresses) but also on the system's sensitivity and resilience when encountering such hazards[[91]]. Therefore, ecological fragility assessments should consider the interrelationships within human–environment coupled systems and the fragility of both the systems and their surrounding environments. Although the natural environment is typically regarded as the primary response factor, numerous studies have shown that both natural and anthropogenic factors serve as key drivers or stressors of ecological fragility[[92]]. While various models and methods exist for assessing ecological fragility, no uniform criteria have been established for parameter selection. Existing studies typically assess the impact of human activities on ecological environments with indicators such as temperature, vegetation index, land use, land cover, precipitation, slope, population density, surface humidity, and vegetation cover[[93]]. Obtaining data on some of these indicators, which measure the objective state of the rural community's ecosystem, such as temperature, precipitation, and surface humidity, is difficult. This study uses population density as an indicator of ecological pressure to assess ecological fragility. Generally, the greater the degree and likelihood of natural pressures and human disturbances affecting an ecosystem's subsystem, the higher the ecological fragility of that ecosystem. High population density correlates with increased human interference in natural resources, contributing to ecological degradation[[94],[95]].

Formal institutions (*Formal*). This study utilizes government finance-related indicators to quantify the formal institutional environment, including fiscal expenditure as a percentage of GDP, government consumption as a percentage of GDP, and fiscal revenues as a percentage of fiscal expenditures[[96],[97]]. Fiscal support is considered an incentive-type institutional factor, where the structure and proportion of fiscal expenditures reflect the level

of regulatory intensity[[98]]. Public financial expenditure and transfer payments are mandatory policy tools that ensure resource allocation to backward regions[[99]]. This study uses the proportion of fiscal expenditure on agriculture, forestry, and water relative to the county in which the rural community is located to measure the formal institutions.

Informal institutions (*informal*). Informal institutions refer to the unwritten rules that shape human behavior but fall outside governmental jurisdiction and formal legal frameworks. These private mechanisms, which guide daily interactions and influence regional lifestyles, encompass social norms, customs, attitudes, moral values, and enforcement practices[[60]]. Li et al. (2023) argue that informal institutions constitute a distinct cultural environment formed by the interaction of informal rules, customs, and values[[99]]. Consequently, several studies have used regional culture as a proxy for informal institutional behavior[[47]]. Furthermore, research suggests that informal institutions emerge from long-term social interactions; for instance, Chinese rural society has developed interpersonal networks rooted in clan-based structures. Studies have measured the population proportion with the same surname to assess this[[101],[102]]. This study follows Liang and Wang's (2019) approach[[103]], using a questionnaire to identify whether a "big surname" exists in the rural community (i.e., more than 20% of the population shares the same surname).

Regional industrial structure (*Industry*). This is measured by the share of GDP from the secondary and tertiary industries in the county where the rural community is located.

Regional economic development (*Pergdp*). This is expressed as GDP per capita in the county in which the rural community is located.

Labor outflow (*Labor*). This is measured as the proportion of permanent migrant labor to the total labor force in the rural community[[104]].

Two mechanism variables are identified in this study: locational conditions, which serve as the mechanism variable for economic factors influencing rural sustainability, and land property rights reform, which serves as the mechanism variable for social and institutional factors affecting sustainable rural community development.

Land rights reform process (*Pro*). Measured by whether the community has completed land reform work[[59]].

Location conditions. Measured by the distance from the community to the county seat (***county***), and the distance from the sample community to the township (***town***)[[67],[68]].

In addition to these factors, the study controls for per capita income **(*Income*)** and the number of farm households **(*Family*)**, as significant socio-economic differences exist between the rural communities. Geographic variables are also controlled, as elevation and slope can significantly influence the development of transportation and water infrastructure[[105]]. This study uses community elevation as a proxy for geographic conditions **(*Altitude*)**. The detailed calculation methods for these variables are presented in Table 3.

Table 3 Methods for measuring other variables

Variable		The detailed calculation methods	References
Ecological factor	Ecological fragility(Eco)	Population density per unit area of land	Timmerman (1981)[[90]]; Turner et al. (2003)[[91]]; Beroya-Eitner (2016)[[92]]; Kamran and Yamamoto (2023)[[93]]; Xiao et al.(2023)[[94]]; Xiao et al.(2023)[[95]]
Economic factor	Regional economic development (Pergdp)	The GDP per capita in the county in which the rural community is located	Zhu et al. (2021)[[64]]; Tao et al. (2021)[[65]]; Gemmell et al.(2008)[[66]]
	Regional industrial structure (Industry).	The share of GDP from the secondary and tertiary industries in the county where the rural community is located	
Social institutions factor	Informal institutions (Informal)	whether a "big surname" exists in the rural community (i.e., more than 20% of the population shares the same surname).	Mcnicoll and North (1991)[[60]]; Li et al. (2023)[[99]]; Williamson et al.(2011)[[47]]; Peng, (2004)[[101]]; Ruan and Zheng (2013)[[102]]; Liang and Wang (2019)[[103]]
	Formal institutions (Formal)	The proportion of fiscal expenditure on agriculture, forestry, and water relative to the county in which the rural community is located to measure the formal institutions.	Adlam (1988)[[96]]; Qi and Xu (2017)[[97]]; Yu et al.(2020)[[98]]; Chen and Chen (2014)[[99]].
Labor factor	Labor outflow(Labor)	The proportion of permanent migrant labor to the total labor force in the rural community	Zhang et al. (2023)[[104]]
Mechanism variable	Land rights reform process (Pro)	whether the community has completed land reform work? 1=Yes, 0=No	Bu and Liao (2022)[[59]]
	locational conditions	The distance from the community to the county seat (County), and the distance from the community to the township (Town)	Tian et al.(2021)[[67]]; Ding et al.(2020)[[68]]
Control Variables	Geographic conditions (Altitude)	The elevation of the rural community	Guo et al.(2012)[[105]]
	Per capita income (Income)	Per capita income	

	Number of Households (Family)	The number of farm households

The characteristics of the variables are summarized in Table 4. Statistical analysis indicates significant variation among the sample communities in terms of labor outflow, regional economic and industrial structures, ecological conditions, geographical environments, sustainable development levels, and formal and informal institutional frameworks.

Table 4 Basic statistics of the variables.

Variable	Obs	Mean	Std.	Dev.	Min
y	227	15.35	9.31	1.20	45.06
Labor	227	54.95	17.98	5.66	93.81
Eco	227	310.47	377.00	44.69	4998.95
Industry	227	72.38	10.35	59.74	93.01
Pergdp	227	3.39	1.15	2.16	6.84
Informal	227	0.53	0.50	0.00	1.00
Formal	227	20.58	7.80	0.39	40.84
Altitude	227	1426.61	503.84	450.00	2400.00
Family	227	604.57	415.70	170.00	3098.00
Income	227	1.08	0.32	0.55	3.00

4 Analysis of factors influencing the level of sustainable development in rural communities

4.1 Benchmark regression results

Before conducting the empirical analysis, this study used robust standard errors in the regression process to ensure the reliability and robustness of the results. Table 5 shows that the variance inflation factor (VIF) values for each explanatory variable in the model are significantly less than 10, indicating that multicollinearity is not a major issue.

Table 5 Multiple covariance test results.

Variable	VIF	1/VIF
Industry	5.14	0.194457
Pergdp	3.9	0.256527
Altitude	2.69	0.371166
Informal	1.91	0.523768
Formal	1.58	0.632317
Income	1.5	0.667969
Eco	1.37	0.729506
Family	1.14	0.873638
Labor	1.12	0.890612
Mean VIF	2.26	

The study begins with a benchmark regression analysis, building on the model setup outlined in the previous section. To better assess the impact of the core explanatory variables on the sustainable development of rural communities, the core variables—*Eco, Industry, Pergdp, Informal, Formal, and Labor*—are sequentially introduced into the model under robust standard error conditions, along with relevant control variables. The results are as follows (Table 6)

Table 6 Basic regression results.

	(1)	(2)	(3)	(4)
Labor	−0.0711*	−0.0752**	−0.0725**	−0.0814**
	(−1.95)	(−2.14)	(−2.06)	(−2.28)
Eco		−0.0054**	−0.0063**	−0.0064***
		(−2.46)	(−2.54)	(−2.86)
Industry			−0.0747	−0.1524
			(−0.45)	(−0.93)
Pergdp			3.6508**	4.3792**
			(2.28)	(2.53)
Informal				−4.1579**
				(−2.12)
Formal				0.0568
				(0.40)
Altitude	0.0058**	0.0061**	0.0067***	0.0051*
	(2.35)	(2.49)	(2.68)	(1.82)
Income	0.6888	1.2102	0.6554	1.0579
	(0.32)	(0.58)	(0.31)	(0.48)
Family	−0.0016	0.0010	0.0006	−0.0001
	(−0.84)	(0.45)	(0.26)	(−0.05)
_cons	14.9104***	14.7113***	6.7634	13.9967
	(3.65)	(3.67)	(0.60)	(1.24)
City	YES	YES	YES	YES
N	227	227	227	227
Adj-R^2	0.0418	0.0722	0.0873	0.1002

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively, and numbers in parentheses are t-values.

The effects of labor outflow. At the 5% significance level, the estimated coefficient for labor outflow on the sustainable development of rural communities is −0.0814. This suggests that labor outflow has a significant impact on hindering sustainable development in rural communities. Specifically, for every 1% increase in labor outflow, the sustainable development of rural communities in ecologically fragile areas declines by 8.14%. This finding is consistent with the studies of Xiao et al. (2021) and Zhou et al. (2020)[[106],[107]], who observed that villages in the ecologically fragile southwestern mountainous regions of China are particularly affected by outmigration, particularly among younger members. In most rural areas within ecologically fragile regions, traditional agricultural practices such as crop cultivation and animal husbandry remain the dominant economic activities, resulting in relatively high labor demands. However, substantial labor outmigration has led to increasingly acute developmental challenges, including labor shortages and rising labor costs. Due to the mountainous terrain, machinery cannot replace labor in promoting agricultural modernization, and the aging population exacerbates land abandonment, leading to a decline in livestock farming.

The effects of ecological fragility. With an estimated coefficient of −0.0064, the degree of ecological fragility passes the 1 %

significance test. This suggests that ecological fragility inhibits the sustainable development of rural communities, with a 0.64% decline in sustainable development for every 1% increase in ecological fragility. This finding is consistent with previous research by Zou and Yoshino (2017)[[108]], Xue et al. (2019)[[109]], and Kang et al. (2018)[[110]], which highlighted the ongoing fragility of ecosystems in China's ecologically fragile areas. The underlying causes of these challenges can be attributed to two key aspects. On the one hand, in ecologically fragile regions such as Guizhou—characterized by rock desertification—the ecosystem recovery cycle is relatively prolonged. Remote geographical areas continue to face the risk of renewed rock desertification, implying that the constraints imposed by ecological fragility on rural areas are a long-term reality. On the other hand, although ecological compensation mechanisms established by the Chinese government have alleviated the conflict between rural economic development and environmental protection, income derived from subsidies and transfer payments is insufficient to ensure the sustainability of rural livelihoods. Consequently, some farming households remain dependent on subsistence practices such as logging, grazing, and cultivation[[111]].

The effects of regional economic development vs. industrial structure. With an estimated coefficient of 4.3792, regional economic development shows a significant positive relationship with the sustainable development of rural communities at the 5% significance level. This suggests that rural communities in ecologically fragile areas experience improved sustainable development as the regional economy develops. This result supports the findings of Li et al. (2022)[**Error! Reference source not found.**], which emphasize the positive effects of regional economic growth on rural development, particularly when infrastructure projects, such as transportation, water conservation, and rural production networks, are implemented. The estimated coefficient for regional industrial structure is −0.1524, which does not pass the significance test. This result suggests that the regional industrial structure has a certain inhibitory effect on the sustainable development of rural communities in ecologically fragile areas. This finding is consistent with those of Yang et al. (2023)[[112]], who noted that the direct impact of the secondary and tertiary sectors on rural revitalization is weak. Upgrading the industrial structure in these areas is challenging, and non-agricultural industries are underdeveloped. Consequently, the influence of industry and services on agriculture is insufficient to provide rural communities access to higher-quality resources via the tertiary sector.

The effects of formal vs. informal institutions. The informal

institutions show a significant negative effect at the 5% significance level, with an estimated coefficient of −4.1579. This indicates that the informal institutions significantly inhibit the sustainable development of rural communities. The estimated coefficient for the formal institutions is 0.0568, which does not pass the significance test. This result is similar to the findings of Zhang et al. (2022)[[114]], who reported that Chinese rural societies increasingly form pluralistic, interest-centered, and "open" social networks. The migration of populations has led to the erosion of traditional village culture, customs, and spiritual space, diminishing the influence of informal institutions on values and kinship cohesion[[115]]. As younger, migrating individuals weaken their social ties to the village, they are less likely to participate in public affairs [[116]]. Moreover, the rise of the rural market economy has enabled village leaders, who are often entrenched in clan networks, to prioritize their own interests over the collective well-being of their community[[117]]. Conversely, the insufficient provision of effective formal institutions in ecologically fragile areas may explain the failure of formal institutions to promote sustainable rural development effectively. State power is often "suspended" in these areas, leading to more pronounced social problems. While resource input and distribution have become central to state policies in rural areas, the lack of formal rules for resource redistribution, coupled with the pressure on rural cadres to avoid responsibility and assessment, often results in inaction. Additionally, concerns among villagers about uneven resource distribution, rather than scarcity, have become more pronounced. For example, during poverty alleviation programs, non-poor groups sometimes misuse resources, while poor households compete for recognition of their status, contributing to systemic inefficiencies.

4.2. Robustness test

As shown in Table 7, columns (1)– (3) display the results of the robustness regressions. The three models are as follows. (1) Replacement model. The sustainable development score for rural communities, measured in the previous section, is greater than 0. This score is treated as an intercepted explanatory variable when used as the dependent variable for the level of sustainable rural community development, meeting the conditions of the Tobit regression model. Therefore, this study adopts the Tobit model with a lower limit of 0 for investigation. (2) Replacement of explanatory variables. This study recalculates the sustainable rural community development level, substitutes it into the model, and re-performs the regression analysis using the entropy value method. (3) Post-tailoring regression. All continuous variables are shrink-tailed at the

1% and 99% quantiles and re-estimated to exclude the influence of outliers. As seen in the table, the core explanatory variables remain consistent with the structure of the base regression.

Table 7 Robustness analysis results.

	(1)	(2)	(3)
Labor	−0.0814**	−0.0599**	−0.0770**
	(−2.36)	(−2.16)	(−2.21)
Eco	−0.0064***	−0.0046***	−0.0062***
	(−3.45)	(−3.07)	(−2.88)
Industry	−0.1524	−0.1405	−0.1472
	(−0.74)	(−1.13)	(−0.90)
Pergdp	4.3792**	3.3985**	4.3563**
	(2.22)	(2.52)	(2.54)
Informal	−4.1579**	−2.8608*	−4.0543**
	(−2.34)	(−1.93)	(−2.11)
Formal	0.0568	0.0842	0.0529
	(0.33)	(0.76)	(0.38)
Altitude	0.0051*	0.0034	0.0050*
	(1.90)	(1.57)	(1.82)
Income	−0.0001	0.0002	−0.0002
	(−0.05)	(0.13)	(−0.09)
Family	1.0579	1.6419	0.7652
	(0.54)	(0.91)	(0.37)
_cons	13.9967	9.2164	13.7784
	(1.12)	(1.11)	(1.23)
City	YES	YES	YES
N	227	227	227
Adj-R^2		0.1032	0.0979
Pseudo R^2	0.0272		

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively, and numbers in parentheses are t-values.

4.3 Mechanism analysis

4.3.1 Mechanism analysis based on local conditions

Since the regional industrial structure coefficient was not statistically significant in the basic regression model, the analysis focused solely on verifying the impact mechanism of regional economies on the sustainable development of rural communities, treating all other variables as controls[[118]]. This study categorized rural communities based on the median distance to both townships and county centers. Regression results for rural communities near the county are presented in column (1) of Table 8, while results for rural communities farther from the county are shown in column (2). Similarly, results for rural communities near townships are in column (3), and those farther from townships are in column (4). The

results reveal that in communities located farther from townships and county seats, the regional economic coefficient is statistically insignificant. In contrast, in communities situated closer to these centers, the *Pergdp* coefficient is consistently positive and significant at both the 5% and 1% levels. This finding demonstrates that locational conditions constitute a key mechanism through which regional economies affect the sustainable development of rural communities. These results highlight the significance of proximity to townships and counties as a transmission mechanism for regional economic factors that influence rural community sustainability. Proximity to urban and economic centers enhances the development value of rural assets[[65]]. For example, suburban rural communities have benefited from urbanization and industrialization by converting vacant residential land into warehouses and retail spaces, thereby effectively revitalizing local resources[[119]].

Table 8 Mechanism test based on local conditions.

	Distance to County		**Distance to Town**	
	(1)	(2)	(3)	(4)
Pergdp	5.5752**	-8.3687	7.7683***	2.4510
	(2.29)	(-0.98)	(2.93)	(0.63)
_cons	37.1816**	-147.9466	21.3098	-19.9423
	(2.14)	(-1.31)	(1.31)	(-0.80)
control variables	YES	YES	YES	YES
City	YES	YES	YES	YES
N	114	113	122	105
Adj-R^2	0.1091	0.0864	0.1091	0.1802

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively, and numbers in parentheses are t-values.

4.3.2 Mechanism analysis based on the land property rights reform process

As the coefficient for formal institutions in the basic regression model was not statistically significant, this study investigates the rural land property rights reform process as a mechanism variable to understand how informal institutions influence the sustainable development of rural communities. The theoretical analysis, supported by the literature, has already established the relationship between land property rights and community development. The present section focuses specifically on empirically verifying the relationship between informal institutions and the land property rights reform process[[120]]. The study uses the Probit model and the OLS model for empirical analysis. Table 9 displays the effects of informal institutions on land property rights reforms in rural

communities. The informal institutions significantly hinders the progress of rural land property rights reforms, with a significance level of 1%. These results suggest that the rural land property rights reform process is a critical mechanism through which informal institutions influence the sustainable development of rural communities.

Table 9 Mechanism test based on the land property rights reform process.

	OLS	Probit
Informal	−0.2631***	−0.8921***
	(−3.16)	(−2.91)
_cons	−0.4001	−3.0646
	(−0.56)	(−1.47)
Control variables	YES	YES
City	YES	YES
N	227	227
Adj-R^2	0.1783	
Pseudo R^2		0.1660

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively, and numbers in parentheses are t-values.

4.4 Heterogeneity analysis

4.4.1 Membership size heterogeneity

The sustainable development of rural communities can be seen as a form of collective action. Ostrom (1990) argues that the efficiency of collective action is linked to the number of participants: as membership size increases, so do transaction costs associated with collective decision-making[[121]]. Larger groups are also more prone to "free-riding" behavior, which complicates the management of community organizations. This study further divides the sample into two groups for regression analysis based on the size of the members, using the median as the cutoff point. Columns (1) represent the small-scale group, while columns (2) represent the large-scale group. The results are presented in Table 10. The findings show that labor outflow and informal institutions exert a pronounced inhibitory effect primarily on large-scale communities. Regional economic development levels and ecological fragility significantly influence both large and small-scale communities, although the impact is more pronounced in the latter.

Table 10 Tests for membership size heterogeneity.

	(1)	(2)
Labor	-0.0445	-0.1184**
	(-0.78)	(-2.27)
Eco	-0.0154*	-0.0052**
	(-1.71)	(-2.45)
Industry	-0.3969	0.0414
	(-1.19)	(0.11)
Pergdp	8.8847***	5.8916*
	(2.67)	(1.67)
Informal	-1.2903	-5.1595*
	(-0.49)	(-1.74)
Formal	0.4040	0.1120
	(1.28)	(0.39)
_cons	-3.9294	-1.6209
	(-0.19)	(-0.07)
Control variables	YES	YES
City	YES	YES
N	113	114
Adj-R^2	0.1516	0.1344

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively, and numbers in parentheses are t-values.

4.4.2 Heterogeneity of poverty rates

Poverty governance has long been a crucial aspect of social governance in China. The Chinese government has supported impoverished villages through industrial projects and financial assistance[[122]]. However, uneven policy support has led to disparities in resource allocation between poor and non-poor counties, as well as between low-poverty and high-poverty communities, resulting in differing resource bases across rural communities. This study thus examines the variability in sustainable development between low-poverty and high-poverty communities. Columns (1) correspond to low-poverty communities, while columns (2) correspond to high-poverty communities, with the specific results shown in Table 11. The analysis reveals that labor outflow exerts a stronger inhibitory effect on the level of sustainable development in the low-poverty rural communities. In contrast, for high-poverty communities, the regional economic development contributes more significantly to sustainability, while ecological fragility and informal institutions have a stronger inhibitory effect.

Table 11 Tests for heterogeneity in poverty rates.

	(1)	(2)
Labor	-0.0838*	-0.0707
	(-1.77)	(-1.25)
Eco	-0.0029	-0.0154***
	(-1.16)	(-2.97)
Industry	-0.6754**	-0.3913
	(-2.37)	(-1.02)
Pergdp	4.7049*	9.6005**
	(1.86)	(2.03)
Informal	-0.3144	-5.1372*
	(-0.12)	(-1.81)
Formal	-0.0403	0.6879**
	(-0.15)	(2.17)
_cons	51.0703***	-2.0513
	(2.72)	(-0.10)
Control variables	YES	YES
City	YES	YES
N	112	115
Adj-R^2	0.1542	0.2237

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively, and numbers in parentheses are t-values.

5 Conclusion and Prospect

This study examines ecologically fragile areas as a distinctive region, utilizing the SES framework theory to explore the factors influencing the sustainable development of rural communities in such areas. The study uses a normative econometric model to verify the impact mechanisms of the labor force, as well as ecological, economic, and institutional factors, on the sustainable development of rural communities in ecologically fragile areas. The findings indicate that various influencing factors exert differing degrees of impact on the sustainable development of rural communities. Regional economic development promotes the sustainable development of such communities, whereas labor outflow, ecological fragility, and informal institutions have a constraining effect. This conclusion remains robust after a series of sensitivity analyses and endogeneity tests. Moreover, regional economic development enhances the sustainable development of rural communities through locational advantages, while informal institutions hinder this development by impeding the progress in land property rights reform. Specifically, communities with locational advantages experience stronger resource diffusion effects from regional

economic development, facilitating the transfer of external resources such as technology and information to the sustainable development of rural communities. However, as population migration intensifies and modern cultural influences expand, the personal constraints embedded in community informal institutions weaken. The fragmentation of social networks and heightened conflicts of interest reduce members' willingness to participate in land property rights reform, slowing the reform process and ultimately inhibiting community development. Finally, for small-scale communities, the inhibitory effect of ecological fragility and the facilitating effects of regional economic development are more substantial, while labor outflow and informal institutions exert a pronounced inhibitory effect primarily on large-scale communities. For low-poverty communities, labor outflow exerts a more significant inhibitory effect on community sustainability. In contrast, for high-poverty communities, the regional economic development contributes more significantly to sustainability, while ecological fragility and informal institutions have a stronger inhibitory effect.

Beyond the issues of high ecological fragility and ongoing environmental degradation, the sustainable development of rural communities in ecologically fragile areas faces additional challenges, including poverty, population outflow, and the compounded effects of multiple factors, such as natural, ethnic, religious, ecological, and economic factors. These interconnected challenges make the sustainable development of rural communities in ecologically fragile areas particularly complex, requiring further scientific evaluation. First, resolving the conflict between ecological governance and economic development remains a key challenge for achieving sustainable rural development in these areas. Efforts should be made to highlight the value of collective actions in advancing the coordinated management and development of rural natural resources. Community-based units should conduct thorough investigations into the local features of resources, including ecological, cultural, and other assets[[123]]. The development of eco-cultural tourism, utilizing traditional cultural resources, has also emerged as an effective pathway for rural communities in ecologically fragile areas to achieve coordinated industrial and ecological revitalization[[124]]. Second, attention should be given to the role of urban-rural integration in supporting the sustainable development of rural communities. Accelerating the free flow of resources between urban and rural areas and promoting the integrated development of urban and rural industries can activate the rural economy[[125]]. Moreover, effective government planning and policies are crucial for achieving sustainable development in

rural communities. In addition to increasing investment in basic public goods, the government should improve the rural institutional environment, encourage social innovation, and actively engage social organizations in the development process. Lastly, rural communities in environmentally fragile areas must enhance economic opportunities, particularly non-farm employment options, to foster return migration. This is essential, as one of the primary drivers of labor migration in rural areas is the search for better employment and livelihoods.

CRediT authorship contribution statement

Dandan Yang: Writing-original draft, Methodology, Conceptualization; **Wei Zhang:** Writing-review & editing, Visualization, Supervision; **Chengjiang Li:** Writing-review & editing, Formal analysis, Funding acquisition; **Jing Yang:** Writing-review & editing, Formal analysis, Visualization; **Shiyuan Wang:** Formal analysis, Supervision.

Ethical statement

All participants were provided with information regarding the study and gave their written informed consent prior to participation. This study was conducted in compliance with the Declaration of Helsinki and all applicable ethical guidelines. All study participants were fully anonymized before further analysis.

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Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

Data availability

The data sets are not publicly available for privacy reasons, but are available from the corresponding author on reasonable request. Please contact the corresponding author (cjli3@gzu.edu.cn).

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