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Original Paper

Evolution of the Characteristic Ecological Industry for Karst Desertification Control: Insights from the Huajiang Zanthoxylum Industry

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Abstract

Global land degradation poses a serious threat to ecosystem security and the sustainable development of human society, and the proposal of the Land Degradation Neutrality (LDN) target marks a new stage in collaborative governance. In the karst regions of southern China, rocky desertification control is shifting from a singular focus on ecological restoration toward a coordinated transformation integrating "ecological restoration and industrial revitalization," yet the consolidation of governance achievements and regional sustainable development still face severe challenges. Taking the Zanthoxylum industry in the Huajiang research area of Guanling–Zhenfeng, Guizhou Province, as a representative case, this study applies Actor-Network Theory (ANT) and its core concept of the obligatory passage point (OPP). Through in-depth interviews, field investigation, and related methods, it traces the interactive network of human and non-human actors throughout the evolution of the Zanthoxylum industry from 1991 to the present, thereby revealing its dynamic evolutionary mechanisms. The results show that: (1) the rise and decline of the Huajiang Zanthoxylum industry are essentially processes in which a heterogeneous actor network is constructed, stabilized, shifted, and deconstructed around the OPP, and industrial success depends on the effective translation of diverse demands into a shared objective; (2) in the first stage (1991-2009), "large-scale cultivation" served as the OPP, with local governments acting as the core translators to effectively integrate the dual goals of ecological governance and livelihood improvement; in the second stage (2010-present), extreme climatic shocks *and the alienation of cultivation techniques among internal actors led to the breakdown of network consensus, causing the OPP to shift toward "rebuilding quality-based trust and market order"; and (3) the long-term resilience of ecological industries depends on the dynamic maintenance of OPP adaptability and network governance capacity. This requires moving beyond a singular focus on technical restoration and constructing a collaborative governance framework for a "social–ecological network" that emphasizes the agency of non-human actors, cultivates a multi-actor co-governance industrial ecology, and incorporates brand credibility and ecological value into the core elements of translation. This study provides theoretical support for advancing the sustainability of rocky desertification control.*

Keywords

Ecological industry, Actor-network, Zanthoxylum, Karst rocky desertification control

1. Introduction

Land degradation has become a severe challenge threatening ecosystem security and the sustainable development of human society (Jiang et al., 2024; Maestre et al., 2025). To address this crisis, the international community incorporated the goal of "Land Degradation Neutrality" (LDN) into the United Nations Sustainable Development Goals (SDGs) in 2015, marking the entry of global collaborative land degradation governance into a new stage (Jia, 2005). In this context, exploring governance pathways that integrate ecological restoration with economic development, and developing eco-friendly economic models, have become key strategies for achieving the LDN target, alleviating human–land conflicts in ecologically fragile areas, and promoting sustainable rural development (Wang et al., 2019). Ecological industries follow principles such as greenness, participation, and cooperation, and transform ecological advantages into economic advantages through industrial ecologicalization and the industrialization of ecology, thereby providing a solution for degraded land restoration and rural revitalization worldwide that combines positive environmental externalities with economic feasibility (Yan et al., 2024; Zhou et al., 2022).

In China, karst rocky desertification is the most prominent form of land degradation in the southwestern region (Ford & Williams, 2007; Yang, 1990), and is defined as "a land degradation process occurring under fragile karst environmental conditions, in which disturbance and destruction caused by unreasonable human socioeconomic activities lead to severe soil erosion, extensive bedrock exposure, and a substantial decline in land productivity" (Bai et al., 2013). Since the Ninth Five-Year Plan period, the Chinese government has continuously advanced comprehensive rocky desertification control projects and achieved remarkable results, with the area affected by rocky desertification in the southwestern karst region showing a "continuous net decrease" (Yue et al., 2024; GOSC, 2008). However, the consolidation of governance outcomes and regional sustainable development still faces multiple challenges, including the lack of region-specific governance technologies and models, unclear socio-humanistic driving mechanisms, and the urgent need to transform large-scale, low-efficiency planted forests (Canedoli et al., 2022). Therefore, it is particularly urgent to promote a transition in rocky desertification control from a single ecological restoration approach to a coordinated stage integrating “ecological restoration and industrial revitalization” (Baker and García, 2020; Fan et al., 2024). Existing studies have shown that developing ecological industries centered on characteristic economic forest and fruit crops in karst rocky desertification areas can effectively coordinate the relationship between ecological protection and economic development (Chen et al., 2024; Xiong et al., 2022). Promoting rural industrial revitalization in ecologically fragile areas through ecological industries is not only an inherent requirement for consolidating the achievements of rocky desertification control, but also a feasible pathway to resolving the dilemma between “ecological protection and economic development” and achieving comprehensive rural revitalization (Chen et al., 2024; Xiong et al., 2022).

However, the development of ecological industries does not occur overnight; rather, it is a dynamic network-building process jointly constructed through complex interactions among multiple heterogeneous actors, including both human and non-human entities. Traditional linear analysis or single-disciplinary perspectives are insufficient to comprehensively reveal the internal mechanisms underlying their rise and decline. Actor-Network theory (ANT) provides a distinctive and powerful analytical framework for understanding the dynamics of such complex socio-ecological systems (Callon, 1984; Liu et al., 2023). This theory has been widely applied to studies of rural development issues such as rural tourism (Chen & Zhang, 2015; Liang & Zhu, 2020), rural industrial transformation (La et al., 2025), and spatial restructuring (Lu et al., 2023), yielding abundant findings. In tracing the developmental trajectory of rural ecological industries in typical ecologically fragile regions, actor networks, through the process of “translation,” reveal the dynamic logic through which industries evolve from emergence to formation, while also resolving the binary paradox between industrial development and ecological protection. The ecological environment itself is incorporated into the analysis as an actor endowed with agency, thereby illuminating how it constrains and shapes industrial pathways. In particular, ANT provides an effective analytical framework for integrating the multiple forces of farmers, governments, markets, and natural ecosystems (Qi & Zhu, 2025).

Based on the above discussion, this study takes the Zanthoxylum industry in the Huajiang research area of Guanling–Zhenfeng, Guizhou Province (hereinafter referred to as “Huajiang”), as a typical case. Using Actor-Network Theory, the study aims to investigate in depth how an ecological industry originating from rocky desertification control mobilizes and integrates human and non-human actors to construct an alliance network of interests intended to achieve the dual goals of ecology and livelihoods. It further examines how, under the dual pressures of external climatic shocks and internal behavioral alienation, the obligatory passage point of this network dynamically shifts, and how the network alliance moves from stability toward turbulence and differentiation. This paper seeks to reveal the dynamic evolutionary characteristics of ecological industries arising from karst rocky desertification control, with a view to providing theoretical insights and practical references for the coordinated advancement of ecological protection and industrial revitalization in similar ecologically fragile regions.

2. Materials and Methods

2.1 Study Area

The Huajiang research area is located in the Huajiang section of the Beipan River Gorge, at the junction of Guanling Bouyei and Miao Autonomous County and Zhenfeng County in southwestern Guizhou Province (105°36′30″–105°46′30″ E, 25°39′13″–25°41′00″ N) (Fig. 1). It covers six administrative villages, including Bashan Village, Xiagu Village, Mugong Village, and Wuli Village in Huajiang Town, Guanling Bouyei and Miao Autonomous County, as well as Chaeryan Village and Yindongwan Village in Beipanjiang Town, Zhenfeng County. The total area is 5161.65 hm^2, with a total population of approximately 9,000. It is a typical karst plateau canyon region. The area has a subtropical monsoon climate, with a mean annual precipitation of 1100 mm and a mean annual temperature of 18.4°C. Owing to strong surface heating, high mountains, deep valleys, and a relative elevation difference of up to 1000 m between rivers and mountains (elevation range: 450–1450 m), the foehn effect is pronounced. The relatively enclosed topography hinders heat dissipation, while the low vegetation cover and rapid surface warming have together formed a typical karst dry-hot valley environment (Gao & Xiong, 2015). Huajiang is classified as a moderate-to-severe rocky desertification area. Carbonate rocks are widely exposed, karst landforms are highly developed, the terrain is highly fragmented, and bedrock exposure is extensive. At the same time, the karst “dual structure” results in weak water-storage capacity of the land. In recent years, frequent extreme droughts have easily caused crop failures. Arable land resources are insufficient, the soil layer is shallow and discontinuously distributed, and the land has poor water retention and drought resistance. Cultivated land quality is generally low, with a large proportion of medium- and low-quality farmland, resulting in low input–output efficiency of land use, prominent human–land conflicts, and severe rocky desertification development (Cheng, 2021).

In 1991, Huajiang initiated large-scale cultivation of Zanthoxylum to address the increasingly severe rocky desertification problem, and it gradually became a local pillar industry. Its governance model, based on the concept of human–land coordination, has become a typical model for rocky desertification control worldwide. After the extreme drought in 2010, the local government, research institutions, and local elites all explored ways to revitalize the Zanthoxylum industry. To date, however, the alienation of cultivation techniques and dishonest practices among traders has led to declining product quality and a crisis of trust. Although the Zanthoxylum industry has lost its former prosperity, it remains a local pillar industry and continues to play a significant role in promoting the sustained control of rocky desertification in the area.

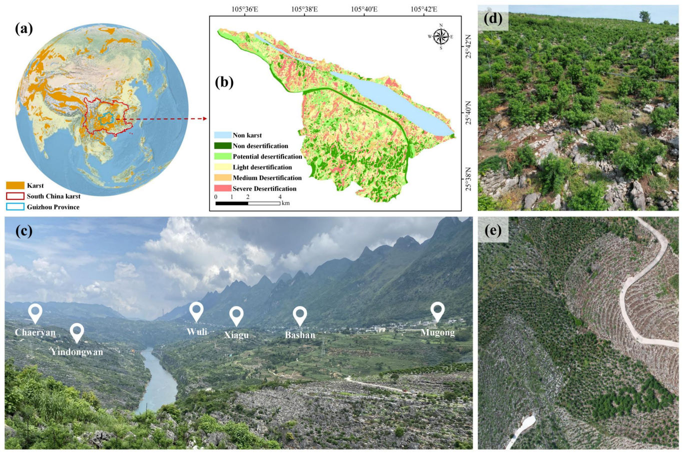

Figure 1. Huajiang Study Area. (a) Global Karst Distribution; (b) Desertification in Huajiang; (c) Dry-hot Valley Landform of Huajiang; (d)–(e) Zanthoxylum Industry

2.2 Data

Relying on our institution's research station in Huajiang Town, the research team conducted a 19-day field survey from October 10 to October 28, 2024. First, through field reconnaissance and the use of unmanned aerial vehicles, among other methods, the team identified the spatial distribution of Zanthoxylum in Huajiang. Subsequently, through in-depth interviews with the village committees of the six villages, the team obtained a comprehensive understanding of the development status of ecological industries in each village, with a particular focus on investigating the origin and development process of the Zanthoxylum industry and documenting key turning points and major conflicts. Second, the production conditions of major Zanthoxylum growers were investigated in detail, and additional information on the development process of the Zanthoxylum industry was collected. Based on these two categories of interviewees, the study further identified all human actors involved in the Zanthoxylum industry and then conducted relevant investigations on the remaining actors one by one. Finally, after organizing all interview materials and drawing on existing research findings and historical data, the study further refined the information on relevant non-human actors and compiled information on the problems, objections, and other issues associated with actors at different stages. The survey covered human actors including village committees, farmers, cooperatives, research institutions, traders, and consumers, yielding a total of 63 questionnaires and more than 600 minutes of audio recordings.

2.3 Methods

Actor-Network Theory (ANT) provides a distinctive perspective for understanding the dynamics of complex socio-ecological systems. Proposed by scholars such as Callon (1984) and Latour (2005), this theory advocates breaking away from the traditional society–nature dualism by placing human and non-human actors on an equal ontological footing and regarding them as agentic "actants." The core of ANT lies in tracing how heterogeneous networks are constructed, maintained, or deconstructed through the process of “translation” among actors, thereby revealing the internal driving mechanisms underlying complex issues such as industrial transformation and environmental governance (Zhang et al., 2024).

The obligatory passage point (OPP) is a key concept in ANT. It refers to the “mandatory passage” established by a focal actor (usually the initiator of a problem) during the process of translation, through which all other actors must pass in order to realize their own interests (Bai et al., 2026; Saito, 2011). The OPP is not only central to problematization, but also serves as a strategic instrument for mobilizing and enrolling actors and for establishing a stable order within the network. By constructing an OPP, the focal actor reframes the diverse and potentially conflicting interests of multiple parties so that they converge under a shared objective, thereby forming a temporary alliance of interests. However, network stability is dynamic. When external conditions or the behavior of internal actors changes, the original OPP may lose its effectiveness, and the network may enter a stage of turbulence and reconstruction (Li & Shao, 2024).

The application of the ANT and OPP framework in this study is highly appropriate. The Zanthoxylum industry in Huajiang represents a typical human–land coupled system in which non-human actors, such as rocky desertified slopes and a dry-hot climate, continuously interact with human actors including local governments, Zanthoxylum growers, and traders. The symmetrical ontology of ANT helps avoid the bias of anthropocentrism. This industry has undergone dramatic fluctuations, from emergence and prosperity to decline and self-rescue. Traditional linear analysis is insufficient to capture the nonlinear causality among multiple factors. By tracing the translation processes and controversies within the actor network, ANT clearly reveals the dynamic shift of the OPP from “large-scale cultivation” to “rebuilding quality-based trust,” thereby explaining how institutions, technology, markets, and ecology co-evolve in a coordinated manner.

3. Results

3.1 Development Process of the Zanthoxylum Industry

Initial stage (1991-1996): Before 1990, maize was the main crop in the Huajiang area of Guanling–Zhenfeng. However, as grain production increasingly expanded onto fragmented and shallow rocky land, soil erosion became progressively more severe. To address this problem, in 1991, the poverty alleviation task force of Qianxinan Prefecture established a working group and conducted in-depth investigations in the Yindongwan and Chaeryan areas. They found that Zanthoxylum had both higher economic returns and soil and water conservation benefits, and began experimental cultivation, which exceeded 600,000 plants by the following year. In 1993, the government of Qianxinan Prefecture allocated RMB 100,000 to establish a Zanthoxylum planting base. By 1996, the planting area had reached 10,600 mu, making it the first ten-thousand-mu Zanthoxylum planting base in Guizhou Province, with per capita income among growers reaching RMB 2,500.

Rapid development stage of Dingtan Zanthoxylum (1997-2009): In view of the success of the “Dingtan model," Dingtan Zanthoxylum began to expand in 1997 to Bashan Village, Xiagu Village, Mugong Village, and other areas, and a "Bangui Zanthoxylum spice base" covering more than 20,000 mu was established in Bangui Township (now Huajiang town). By 2002, to support Zanthoxylum cultivation, and under the auspices of the Ministry of Water Resources in collaboration with institutions including Guizhou Normal University, governance models were developed for the Mugong, Yindongwan, Kongluojing, and Dingtan small watersheds. Five check dams and more than 70 water storage tanks were constructed, with a total water storage capacity exceeding 10,000 m^3, thereby preliminarily solving the water shortage problem for Zanthoxylum cultivation. By 2006, a 15,000-mu high-quality Zanthoxylum seed collection base, jointly funded by the provincial government and the Qianxinan Prefectural Government, was completed, and both Dingtan Zanthoxylum and Bangui Zanthoxylum entered their peak period. In 2008, Dingtan Zanthoxylum was certified as a national geographical indication product, and the planting scale exceeded 35,000 mu.

Decline of Dingtan Zanthoxylum and slow development of Bangui Zanthoxylum (2010-2017): A prolonged drought in the autumn and winter of 2010 severely affected the region. Because the soil layer in Chaeryan Village and Yindongwan Village, where Dingtan Zanthoxylum was grown, was extremely shallow, 20% of the Zanthoxylum trees died, and the remaining trees also suffered varying degrees of damage, resulting in a sharp decline in yield. At the same time, homogeneous competition from Bangui Zanthoxylum and surrounding production areas continuously drove down market prices, pushing Dingtan Zanthoxylum into decline. Some farmers gradually abandoned Zanthoxylum cultivation and began planting other crops, although some persisted. In contrast, in Mugong Village, Bashan Village, Xiagu Village, Wuli Village, and other areas where Bangui Zanthoxylum was grown, the relatively thicker soil layer allowed most saplings to survive. Bangui Zanthoxylum gradually became the core of regional Zanthoxylum production. However, homogeneous production and competition from Zanthoxylum produced in other regions led to a gradual market downturn, and the industry no longer retained its former prosperity.

Decline and self-rescue (2018-present): The original cultivation system had relatively low yields. In order to obtain greater production and revitalize the Zanthoxylum industry, in 2018 the local government organized more than 600 Zanthoxylum growers to study cultivation techniques in Chongqing, Sichuan, and other areas. It also attempted to build a ten-thousand-mu Zanthoxylum base in Bashan Village to radiate development across the entire region and to replant Zanthoxylum trees that were approaching the end of their life cycle. Zanthoxylum yield began to increase and showed a tendency to regain its status as a leading industry. In 2020, however, the COVID-19 pandemic affected the entire market, and the Zanthoxylum industry entered a period of stagnation. By 2022, although the market had begun to recover, an increasing number of growers adopted a new cultivation technique—stumping—in pursuit of higher yields. Although this practice made the trees lush and greatly increased production, the flavor remained inferior to that of Zanthoxylum produced under traditional cultivation methods. At the same time, many local traders brought in Zanthoxylum from other regions and sold it locally under the brands of Bangui Zanthoxylum and Dingtan Zanthoxylum, seriously disrupting the market and substantially undermining purchasers' trust in these two brands. By September 2024, the price of fresh Zanthoxylum had fallen to RMB 7 per jin. At present, in the Huajiang research area of Guanling–Zhenfeng, only some large-scale growers continue to invest in Zanthoxylum cultivation, while most growers have shifted to an "extensive management" mode and have gradually resumed maize cultivation.

3.2 Translation of the Actor Network

(1) Human actors

Local governments (government bodies at the prefectural, county, township, and village levels), cooperatives, Zanthoxylum growers, research institutions (Guizhou Normal University), Zanthoxylum purchasers, and consumers.

Driven by the dual goals of improving regional livelihoods and restoring the ecological environment, local governments formulated a plan for large-scale Zanthoxylum cultivation after extensive investigation. Villagers, mainly from Yindongwan Village and Chaeryan Village, became the earliest Zanthoxylum growers and the first beneficiaries, while the cooperative model further strengthened production support and unified management. During this process, research institutions, primarily represented by Guizhou Normal University, worked under the leadership of local governments and in collaboration with multiple other research institutions to continuously tackle key challenges in Zanthoxylum production, including water storage, yield improvement, and water–fertilizer coupling. Zanthoxylum purchasers became the link between products and the market, while consumers served as providers of feedback on product quality and played an important role in shaping the Zanthoxylum brand.

(2) Non-human actors

Capital, rocky desertified slopes, climate, and transportation and water-resource infrastructure.

Funds investment was a key input in the initial stage of Zanthoxylum production and became crucial support for several rounds of scale expansion and infrastructure improvement. Rocky desertified slopes provided the physical space for Zanthoxylum cultivation, while the special climate of the dry-hot valley became a decisive condition for the distinctive flavor of Dingtan Zanthoxylum under traditional cultivation practices. Meanwhile, improvements in transportation and water-resource infrastructure became necessary prerequisites for scaling up the Zanthoxylum industry, particularly the latter, the resolution of which became essential for the long-term sustainability of the industry.

(3) Problems

Stage I: 1991–2009

Local governments: Market demand was strong, and further expansion of production scale was still needed.

Cooperatives: Increase membership and maintain the stability and growth of the cooperatives.

Villagers: They were not satisfied with the existing benefits.

Research institutions: There was an urgent need to expand the industrial model andtechnological demonstration achievements of the Zanthoxylum industry in order to showcase research outcomes.

Zanthoxylum purchasers and consumers: Market prospects were favorable, supply fell short of demand, and more products were needed.

Funds: The funds required for scale expansion were excessive and heavily dependent on local government fiscal input.

Desertified slopes: Soil erosion still required continuous control.

Climate: Drought risk persisted, and technologies for coping with climate change needed to be developed.

Infrastructure: Facilities were inadequate in the context of scale expansion.

Geographical indication brand: A geographical indication brand was lacking, and brand effects needed to be obtained.

Stage II: 2010–present

Local governments: Fiscal resources were insufficient to resolve the predicament of large-scale disaster impacts facing the Zanthoxylum industry.

Cooperatives: Maintain the cooperative model and ensure normal production.

Villagers: With the market disrupted and depressed, they had to weigh the choice between continuing cultivation and withdrawing from it.

Research institutions: Fluctuations in Zanthoxylum yield caused by extreme climate and fluctuations in product quality caused by the stumping technique remained difficult challenges to overcome.

Zanthoxylum purchasers: Some traders deceived the market and disrupted market order, thereby undermining the interests of merchants operating legally and in compliance with regulations.

Consumers: It was difficult for them to obtain genuinely high-quality traditional Zanthoxylum.

Funds: Early-stage investment, scale expansion, and related processes all depended on government fiscal support, indicating heavy reliance on public finance and a lack of relevant enterprise participation.

Desertified slopes: Withdrawal from the Zanthoxylum industry could expose the problem of rocky desertification once again.

Climate: Climatic conditions were no longer stable, and extreme climatic fluctuations became an important factor stifling the industry.

Infrastructure: The downturn of the Zanthoxylum industry made it impossible to recover sufficient funds to improve facilities.

Geographical indication brand: The credibility of the product brand came under question.

The obligatory passage point (OPP) of the Zanthoxylum industry in Huajiang was dynamic. In the first stage (1991-2009), “large-scale Zanthoxylum cultivation,” under the dual goals of rocky desertification control and livelihood improvement, constituted the OPP that all actors needed to overcome. All actors needed to promote industrial scale expansion in order to generate returns for human actors, satisfy the needs of all parties, and use surplus funds to address the problems faced by non-human actors, especially infrastructure improvement and rocky desertification control. In the second stage (2010–present), climatic and market factors, among others, constrained the sustained development of the Zanthoxylum industry. In particular, local governments, as the core actors, lacked sufficient fiscal capacity to resolve the relevant problems. The OPP thus shifted to “establishing and maintaining an industrial collaboration system capable of ensuring Zanthoxylum quality, resisting climatic risks, and winning market trust.” The trade-off faced by Zanthoxylum growers between yield and quality, the competition between illegal non-local traders and local traders committed to preserving quality, and the continued efforts of research institutions to address the challenge of healthy Zanthoxylum growth under unstable climatic conditions have all become crucial to reshaping the future development pattern of the Zanthoxylum industry (Fig. 2).

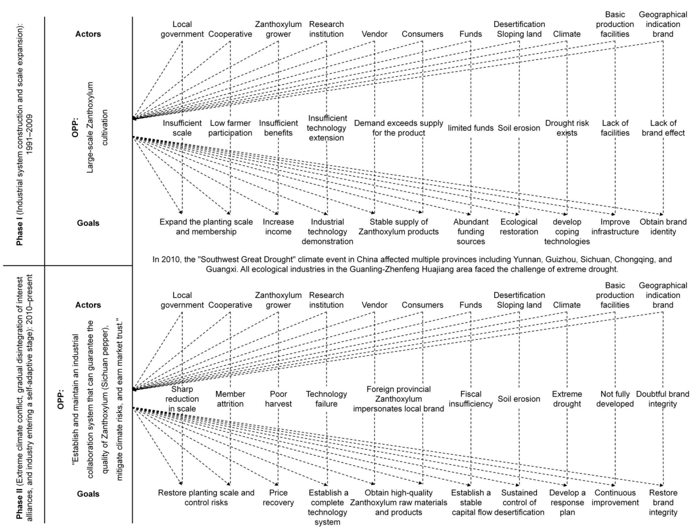

Figure 2. Problems and OPP Faced by Actors in the Zanthoxylum Industry

(4) Enrollment and Mobilization

The enrollment and mobilization of Zanthoxylum cultivation in the Huajiang research area occurred across multiple stages and involved multiple actors. In the initial stage of Dingtan Zanthoxylum cultivation, with the “local government” serving as the core translator, cooperatives, Zanthoxylum growers, and research institutions were enrolled or mobilized; through the exercise of its administrative authority, non-human actors such as capital, infrastructure, and barren slopes were also enrolled. Meanwhile, through the leading role played by village cadres and the high returns generated by the first batch of Zanthoxylum products, doubts over whether Zanthoxylum cultivation could be profitable were resolved, prompting more villagers to join Zanthoxylum cultivation voluntarily and subsequently bringing in villagers’ capital and sloping land. At the same time, through research institutions, drought-response technologies and water–fertilizer coupling technologies for Zanthoxylum cultivation were enrolled. Furthermore, through Zanthoxylum products, traders and consumers were enrolled into the network. In 2002, in order to develop the industry and meet the interests and demands of farmers in the Bangui area, the government took the lead in mobilizing villagers to establish the Bangui Zanthoxylum industry in areas now including Wuli Village, Bashan Village, Xiagu Village, and Mugong Village. Large-scale expansion created water-use problems, prompting the government to invest substantial fiscal funds and once again mobilize villagers to construct water conservancy facilities. By 2008, with the market recognition of large-scale cultivation and Zanthoxylum quality, the geographical indication brand was enrolled. In 2018, in order to revitalize the Zanthoxylum industry, the government once again mobilized growers to learn cultivation techniques in other regions, but this did not bring about the expected revitalization. At the current stage, the Zanthoxylum industry has entered an adaptive phase, in which individual growers have become the basic production units.

(5) Dissidence

During the first two stages of the development of the Zanthoxylum industry, local government became the key core actor leading industrial development, and the industry as a whole showed a thriving trend. By the second stage, especially after 2020, the regulatory role of the government weakened, and industrial development shifted from a cooperative model to individual operation. The trade-off between Zanthoxylum yield and quality became the critical point leading to a crisis of trust in the Zanthoxylum brand. This gave rise to dissidence among human actors, including between consumers and villagers, consumers and illegal traders, local governments and illegal traders, villagers and illegal traders, and villagers adhering to traditional cultivation techniques and those adopting alienated techniques.

"In the past, we did not practice stumping. But after people came back from Sichuan from learning the techniques, some of them started stumping, and then the yield increased a lot. Some trees could produce fifty or sixty jin of fresh fruit. But stumping requires a lot of chemical fertilizer; that little bit of manure is not enough, and quick-acting fertilizer is necessary for higher fruit set. But once you do that, the quality of the Zanthoxylum declines. This kind of Zanthoxylum has a bitter taste, and its aroma is not as good as that of the original Zanthoxylum. Then there are traders who bring Zanthoxylum from Sichuan over here and pass it off as local Bangui Zanthoxylum. Many buyers have become scared and are afraid of buying fake products. In this way, Zanthoxylum is no longer worth much. Those who planted a lot have no good solution—they cannot bear to cut the trees down, so they just continue stumping. As for us, we basically do not plant it anymore; we just harvest whatever is left in the fields."

(6) Formation of the Alliance of Interests

The development trajectory of the Zanthoxylum industry in the Huajiang research area clearly demonstrates a dynamically evolving process of interest alliance formation and actor-network construction centered on the core objectives of "rocky desertification control and livelihood improvement." In the initial stage (the 1990s), under the dual pressures of ecological degradation and poverty, local governments, as the core translators, successfully aligned diverse demands around the obligatory passage point (OPP) of "large-scale Zanthoxylum cultivation." Through capital investment and policy mobilization, they enrolled the first group of Zanthoxylum growers and research institutions, while also incorporating non-human actors such as rocky desertified slopes and the unique local climate into the network, thereby forming a stable "ecology–livelihood" alliance of interests: the government achieved governance outcomes, farmers' incomes increased, and the land was conserved. Entering the expansion stage (around 2000), when "water scarcity" became a new OPP, water management authorities and more advanced research forces were successfully mobilized. The construction of water conservancy facilities further strengthened this alliance, promoting the prosperity of the industry and the certification of geographical indication products. At this point, the network was in a highly coordinated and stable phase. However, from the late 2010s onward, the network encountered successive shocks and entered a period of turbulence and differentiation. Extreme climate, as a powerful non-human actor, directly challenged the resilience of the network and exposed its vulnerability. More critically, internal dissidence and alienation emerged within the network, leading to the breakdown of consensus: some growers introduced the stumping technique in pursuit of higher yields at the expense of flavor quality, while some purchasers sought short-term gains by passing off Zanthoxylum from other regions as local products. Together, these actions eroded the quality reputation embodied in the key non-human actor of the "Dingtan/Bangui Zanthoxylum" brand and undermined consumer trust. At this stage, the OPP of the network had shifted to "rebuilding a credible system of quality assurance and market order." However, the mobilizing capacity of the core translator (local government) had relatively weakened, and the industrial organization had retreated from the cooperative model to individualized "extensive management," with the network evolving from a tightly knit alliance into a loose structure of strategic interaction.

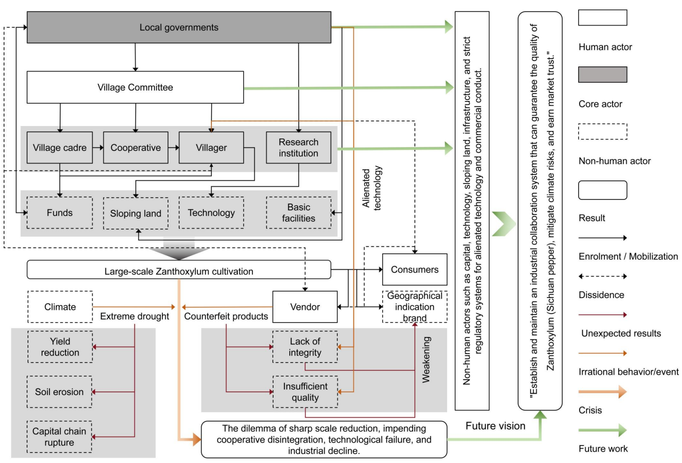

Figure 3. Actor-Network of the Zanthoxylum Industry

4. Discussion

4.1 Revitalizing the Zanthoxylum Industry

A "geographical indication brand revitalization" initiative should be launched to reconstruct the core value of the industry. Traditional cultivation protocols for Dingtan Zanthoxylum and Bangui

Zanthoxylum that exceed national standards should be formulated and strictly enforced, while a full-chain traceability system should be established. Technological alienation practices that damage flavor quality, such as stumping, should be strictly prohibited. A publicly accessible inquiry platform should be established, and law enforcement agencies should work jointly to crack down rigorously on counterfeit and substandard products, thereby establishing “compliance and authenticity” as the obligatory passage point (OPP) for industrial recovery. An ecological premium market strategy should also be implemented. Dingtan Zanthoxylum should be positioned as a “premium original-flavor” product, with emphasis placed on the uniqueness of its native habitat, while high-end gift packaging and flavor extracts should be developed. Bangui Zanthoxylum should be positioned as an “eco-premium” product, with efforts directed toward expanding channels for mass consumption and deep processing. In addition, a “brand guardian alliance” composed of the government, cooperatives, and farmers committed to traditional cultivation should be established. Honest traders should be incorporated into an authorized distribution system, while a blacklist mechanism should be introduced to eliminate dishonest actors from the market.

A “multi-actor co-governance” industrial actor network should be reconstructed in order to cultivate endogenous development momentum. The role of government should shift from that of a direct leader to that of a rule maker and order maintainer, while “chain-leading” enterprises integrating standards setting, technological research and development, purchasing and processing, and brand marketing should be cultivated as the new core of the network. A close contractual alliance of “chain-leading enterprises + cooperatives + farmers” should be established to enable risk sharing and benefit sharing. In response to the rigid constraint of shallow soil in the original production area of Dingtan Zanthoxylum, innovative ecological compensation mechanisms should be developed to link rocky desertification control funds and carbon sink revenues with the renewal of old Zanthoxylum orchards and ecological stewardship. An industrial resilience development fund and an extreme climate early warning mechanism should be established, and ecological protection performance should be linked to industrial support policies so as to prevent the rebound of rocky desertification risk. In addition, pathways for integrating the Huajiang Grand Canyon Scenic Area with the forest-fruit industry should be expanded, transforming Zanthoxylum orchards and fruit orchards into sightseeing and experiential resources, and promoting the extension of brand value from agricultural products to ecological and cultural services.

4.2 Limitations of the Study

This study is based on a single representative case. Although it enables an in-depth examination of the dynamic details of actor-network translation, the generalizability of its conclusions to other ecological industries in karst areas or to different socio-economic contexts remains to be tested. In addition, the study mainly relies on retrospective interviews and historical materials, resulting in insufficient real-time tracking of network evolution. The “agency” of non-human actors is also difficult to observe and quantify directly in theoretical interpretation, which may entail the risk of subjective construction by the researcher. Future studies could adopt multi-case comparative or longitudinal tracking designs and combine methods such as remote sensing monitoring and soil physicochemical analysis to enhance the objectivity of evidence regarding the role of non-human actors. At the same time, Social Network Analysis (SNA) could be introduced to quantify the strength of relationships among actors and the evolution of network structure, or ANT could be brought into dialogue with resilience theory and governance theory to explore differences in the resilience of ecological industry networks under different governance models. Finally, how to translate intervention strategies such as “geographical indication brand revitalization” into operational policy simulation models is also a direction worthy of further in-depth exploration.

5. Conclusion

This study applies Actor-Network Theory to trace the more than 30-year evolutionary trajectory of the Zanthoxylum industry in Huajiang and to reveal the internal dynamic mechanisms of ecological industries emerging from karst rocky desertification control. The findings show that the rise and decline of the industry are essentially processes in which a heterogeneous actor network is constructed, stabilized, and deconstructed around the obligatory passage point (OPP). In the initial stage, local governments, as the core translators, aligned the demands of rocky desertification control and livelihood improvement around the OPP of “large-scale cultivation,” successfully enrolling Zanthoxylum growers, research institutions, water conservancy facilities, and even rocky desertified slopes and the unique local climate, thereby forming a stable “ecology–livelihood” alliance of interests. However, extreme drought undermined the resilience of the network, and more importantly, internal dissidence and alienation emerged: some growers overused the stumping technique at the expense of product quality, while traders profited from counterfeit products. Together, these actions eroded the credibility of the geographical indication brand, causing the OPP to shift toward “rebuilding quality-based trust.” At the same time, the mobilizing capacity of the government weakened, and the network degenerated from a tightly knit alliance into a loose structure of strategic interaction. The long-term resilience of ecological industries depends not only on initial restoration and scale expansion, but also on the dynamic maintenance of OPP adaptability and network governance capacity. In the future, it is necessary to move beyond a single-minded focus on technical restoration, incorporate non-human actors such as brand trust into the core process of translation, and construct a collaborative network of multi-actor co-governance in order to achieve a fundamental transformation from “consolidated governance” to “sustainable revitalization.”

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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