

Article

Forest Ecological Product Value and Farmers' Livelihoods in China: A Dynamic Assessment of Synergy and Mismatch

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Abstract

The realization of forest ecological product value has been promoted as an important pathway for reconciling ecological conservation with rural prosperity. However, it remains unclear whether the growth of forest ecological product value has been synchronized with improvements in farmers' livelihoods. Using panel data from 31 Chinese provinces from 2011 to 2022, this study develops an integrated framework combining allometric growth analysis, a Bayesian hierarchical symbiotic coefficient model, a Lotka–Volterra interaction model, a multi-period difference-in-differences design and LightGBM-SHAP interpretation. The results show that 87% of provinces exhibit negative allometric growth, indicating that forest ecological product value has generally grown faster than farmers' income. The national symbiotic coefficient increased before 2019 but declined thereafter, suggesting a weakening ecological-livelihood synergy. The multi-period DID results indicate that the 2017 Green Finance Reform and Innovation Pilot Policy significantly weakened the symbiotic relationship in pilot provinces. LightGBM-SHAP further shows that financial development, technological progress and transportation infrastructure are key variables associated with symbiotic equilibrium, with substantial regional heterogeneity. These findings suggest that ecological product value realization and green finance do not automatically translate into inclusive livelihood benefits. More targeted benefit-sharing, financial transmission and farmer-participation mechanisms are needed to promote forest-based ecological prosperity.

Keywords: forest ecological product value; farmers' livelihoods; symbiotic coefficient; allometric growth; green finance; difference-in-differences; LightGBM-SHAP

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1. Introduction

Forests are central to sustainability transitions because they connect ecological security with rural development. As natural capital, forests support biodiversity conservation, carbon sequestration, climate regulation, water conservation, soil retention and other ecosystem services that underpin human well-being [1,2]. As livelihood assets, they also provide income opportunities through forestry production, non-timber forest products, understory economies, ecological tourism and forest-based health services, especially in mountainous and ecologically sensitive regions [3]. Forest ecological product value, which can be defined as the total economic value of both tangible products (e.g., timber and non-timber forest products) and intangible public-good services (e.g., water

conservation, carbon sequestration, soil retention, air purification, biodiversity maintenance, and recreational services) provided by forest ecosystems, captures this dual contribution. The valuation of ecosystem services and gross ecosystem product (Gross Ecosystem Product (GEP), proposed by Chinese scholars (Ouyang et al.), measures the total annual monetary value of ecosystem services—material provision, regulation, and cultural services—delivered to human well-being within a region. It serves as an ecological counterpart to GDP and has been adopted in China's policy framework for ecological performance assessment and eco-compensation) (GEP) provides an important way to make the contribution of nature visible in policy and economic decision-making [4–6]. In China, large-scale investment in natural capital and land-system restoration has improved several ecosystem services and created institutional conditions for ecological product value realization[7] . The realization of forest ecological product value is therefore expected to become a key pathway through which ecological resources can be transformed into development opportunities for rural areas [8].

Although this study focuses on China's institutional context, the relationship between forest ecosystem services, conservation finance, and rural household welfare has attracted growing scholarly attention well beyond China, particularly in the Global South. Research has documented substantial contributions of forest ecosystem services to rural livelihoods. Ahammad et al. [9], drawing on 300 household interviews in Bangladesh's Chittagong Hill Tracts, demonstrated that forest ecosystem services contribute significantly to household income portfolios, with provisioning services playing a particularly vital role. Similarly, Langat et al. [10], found that forest income accounts for approximately 43.4% of household income in Kenya's East Mau forest ecosystem, while Chettri et al. [11] reported that forest ecosystems provide the maximum share of ecosystem services in the Eastern Himalaya. These findings underscore that forests function as critical livelihood assets across diverse ecological and institutional settings, although the mechanisms through which ecological value translates into household welfare vary markedly with market access, tenure arrangements and policy frameworks.

Beyond provisioning and regulating functions, forests provide substantial cultural ecosystem services that contribute to human well-being through recreation, aesthetics, spiritual enrichment and mental health restoration. Wolf et al. [12], in a comprehensive scoping review, documented the multiple pathways through which urban trees and forests influence human health, concluding that urban forest planning should strategically promote trees as a social determinant of public health. Hedblom et al. [13] demonstrated through a multisensory virtual experiment that exposure to urban green spaces, including urban forests, significantly reduces physiological stress. In the European context, O'Brien et al. [14] examined the ecological functions and human benefits of urban forests, finding that these ecosystems deliver a wide range of cultural services that enhance quality of life in anthropogenic environments. These studies collectively highlight that the value of forest ecosystems extends far beyond material products and regulating services to encompass intangible contributions to human well-being that are increasingly recognized in ecosystem service assessments. Yet the direct conversion of these cultural benefits into rural household income remains less systematically examined.

The perception of forest ecosystem services by visitors and local residents has emerged as an important dimension of ecosystem service assessment, particularly for cultural services that depend on human experience and appreciation. Crețan et al. [15] investigated visitors' perceptions of forest ecosystem services in the urban and peri-urban spaces of Timișoara, Romania, finding that recreational and aesthetic services were most highly valued by visitors. Hegetschweiler et al. [16] compared urban forest usage and ecosystem service perception between teenagers and adults in Switzerland, reveal-

ing significant intergenerational differences in the recognition and valuation of cultural ecosystem services. Wang et al. [17] examined visitor perceptions and motivations as drivers of cultural ecosystem services in Helsinki's urban forests, concluding that nature-orientation and tangible benefits such as physical health were strongly associated with cultural ecosystem service demand. These perceptual studies are particularly relevant because they illuminate the demand side of ecosystem services, complementing supply-side assessments and helping to identify the specific pathways through which forest ecological product value can be realized. However, they rarely address whether the economic surplus generated by these services is effectively captured by local farmers.

Consequently, forest ecological product value does not necessarily translate into synchronous livelihood improvement. Studies on forests, livelihoods and conservation have shown that ecological conservation and household welfare may interact in multiple and sometimes conflicting ways [18,19]. Forest conservation and ecological restoration may increase the supply of ecosystem services, but local households may not benefit sufficiently if market access, property-right arrangements, benefit-sharing mechanisms, ecological compensation standards, green finance support or participation channels are incomplete [20,21]. Conversely, farmers' livelihood activities may either strengthen forest ecological product value through sustainable management or weaken it through excessive extraction, low-value commercialization and poorly regulated development [22]. The relationship between forest ecological product value and farmers' livelihoods should therefore be understood not as a simple linear linkage, but as a coupled socio-ecological interaction in which the two systems may reinforce, constrain or offset each other [23].

Existing studies furnish an important foundation for this argument. That forests and other natural resources contribute substantially to rural livelihoods—particularly in forest-dependent and low-income communities—is well documented. Equally instructive is the literature on payments for ecosystem services and eco-compensation (eco-compensation in China combines ecological compensation and PES.), which suggests that ecological protection policies can support poverty reduction, provided that compensation standards, participation rules and alternative livelihood arrangements are carefully designed [24]. Yet these same studies caution against assuming that ecological policies automatically yield inclusive income benefits. Welfare impacts, they note, vary markedly across regions, projects and income groups. Indeed, where poor households confront participation barriers, high opportunity costs or weak market access, such policies may deepen rather than reduce inequality [25,26]. Consequently, the central question is not merely whether forest ecological product value correlates with farmers' income, but whether the growth of ecological value can be translated into livelihood improvements that are stable, inclusive and mutually reinforcing [27].

The cultural dimensions of forest ecosystem services deserve particular emphasis given their growing importance in ecological product value realization. Forests serve as important settings for nature-based tourism, forest therapy, and recreational activities that generate both economic value and human well-being outcomes. Huynh et al. [28], linking the nonmaterial dimensions of human-nature relations with human well-being through cultural ecosystem services, demonstrated that nature-based recreation in forests and woodlands fosters both psychological well-being and pro-environmental attitudes. Paletto et al. [29] conducted a quantitative literature review on forest-based practices for human well-being, identifying forest therapy, forest bathing, and nature-based rehabilitation as emerging modalities that leverage the cultural services of forests for health outcomes.

Visitor perception research further illuminates how cultural ecosystem services are experienced and valued in different forest contexts. Bertram & Rehdanz [30] compared

attitudes, perception, and use of cultural urban ecosystem services across park visitors, finding that the perceived importance of ecosystem services often exceeds their actual provision, creating demand–supply mismatches that policy must address. Duşcu & Rîşnoveanu [31] examined visitor preferences regarding anthropogenic and natural forest features in supplying cultural ecosystem services, concluding that both natural attributes and management interventions shape visitor experience. Derks et al. [32] recorded visitor perceptions of cultural, recreational, and aesthetic ecosystem services in Bonn’s urban forests before and during the COVID-19 lockdown, documenting significant shifts in service appreciation during periods of restricted mobility. Zhang et al. [33] used social media data to rethink cultural ecosystem services in urban forest parks, analyzing citizens’ physical activities to reveal how aesthetic and recreational services are consumed in practice. These perception studies are essential for understanding the demand-side dynamics of forest ecological product value realization, as they identify which specific services visitors value most and how these preferences translate into economic opportunities for forest-dependent communities.

This empirical and policy issue is particularly relevant in China, where an evolving legal and policy architecture has sought to institutionalize the conversion of ecological assets into economic and social benefits. Over recent decades, China has promoted large-scale ecological restoration, eco-compensation, collective forest reform and green finance policies to improve ecosystem services and support rural revitalization [34]. Empirical evidence suggests that national ecological programs and investments in natural capital have improved several ecosystem services, although their ecological and socioeconomic effects may differ across space and time [7,35]. Evidence from the Sloping Land Conversion Program and other PES programs further indicates that policy impacts on household income, labor allocation and land use are often heterogeneous and pathway-dependent [25]. The policy agenda of ecological product value realization reflects China’s attempt to institutionalize the conversion of ecological assets into economic and social benefits [6,36]. More recently, green finance reform and innovation pilot zones have been expected to guide financial resources toward ecological protection, green industries and ecological product value realization [37]. In 2017, China formally established green finance reform and innovation pilot zones. Green finance is defined as a financial service system that supports environmental improvement, energy conservation and emission reduction, and efficient resource utilization, guiding green capital allocation through instruments such as green credit, green bonds, and green insurance [38]. These pilot zones constitute policy experimental areas designed to advance green finance development and promote industrial green transformation, with the aim of exploring replicable and scalable green financial institutions and practical experience. China’s approach to forest ecological product value realization and farmer livelihood improvement is shaped by a multi-layered legal and policy architecture. At the legislative level, the Forest Law of the People’s Republic of China establishes the forest ecological benefit compensation system, mandating strengthened support for public welfare forest protection and improved transfer payment policies for key ecological function zones. The forthcoming Eco-Environment Code (effective August 2026) further institutionalizes the ecological product value realization mechanism, and explicitly strengthens financial support for ecological conservation through green credit, green bonds, green insurance, and green trust products. The Ecological Protection Compensation Regulations, China’s first administrative regulation dedicated to eco-compensation, stipulate that the state shall leverage market mechanisms to advance market-oriented ecological protection compensation and expand ecological product value realization models, while improving fiscal, financial, and tax policy measures to support the green finance system.

In the policy domain, the People's Bank of China, the National Forestry and Grassland Administration, and the National Financial Regulatory Administration jointly issued the Notice on Financial Support for High-Quality Forestry Development (2025), which establishes a financial mechanism supporting ecological product value realization and encourages financial institutions to develop innovative financing products for forestry carbon sink resources. The Notice on Leveraging Green Finance to Serve Beautiful China Construction (2024), issued by the PBOC, Ministry of Ecology and Environment, and financial regulators, integrates green financial services into the broader agenda of ecological civilization construction. These policies complement the Action Plan for Establishing Market-based and Diversified Eco-compensation Mechanisms (2018), which explicitly calls for expanding pilot zones for green finance reform and innovation. Together, this evolving legal and policy framework provides the institutional foundation for examining how green finance policies reshape the relationship between forest ecological product value and farmers' livelihoods in China.

Yet policy attention has often focused on expanding ecological assets, improving ecosystem service supply or marketizing ecological products, while less attention has been paid to whether the growth rhythm of forest ecological product value is synchronized with farmers' livelihood improvement. If ecological product value grows faster than farmers' livelihoods, ecological improvement may fail to generate sufficient livelihood benefits. (Livelihood benefits refer to the improvements in households' sustainable livelihood assets—natural, human, physical, financial, and social capital—resulting from ecological policies such as Payments for Ecosystem Services. The concept is commonly operationalized through the Sustainable Livelihoods Framework (SLA) developed by the UK Department for International Development.). If livelihood growth depends on resource depletion, income improvement may undermine ecological sustainability. The scientific question that motivates this study is therefore whether forest ecological product value and farmers' livelihoods are moving toward symbiosis, or whether they are developing in a mismatched manner.

Although previous studies have examined the links between forest resources, ecosystem services, ecological compensation and rural livelihoods, several limitations remain. First, most studies focus on one-way effects, such as how ecological compensation or forest resources influence household income, poverty reduction or livelihood strategies, while the bidirectional and co-evolutionary relationship between forest ecological product value and farmers' livelihoods is still insufficiently measured [18]. Second, much of the existing evidence comes from specific programs, household surveys, counties or case regions, which limits the ability to reveal long-term spatial patterns at the national scale [26]. Third, many studies rely on correlation analysis or average treatment effects, leaving limited evidence on how external policy shocks reshape the dynamic ecological-livelihood linkage. Recent research has begun to evaluate whether green finance policy promotes ecological product value realization or environmental improvement, but it remains unclear whether such policy strengthens the connection between ecological value growth and farmers' livelihood improvement [39,40]. These gaps call for a framework that can jointly examine growth rhythm, interaction direction, policy shocks and regional mechanisms.

Drawing upon symbiosis theory and allometric growth models, this study will use panel data from 31 Chinese provinces from 2011 to 2022 to examine whether forest ecological product value and farmers' livelihoods develop in a mutually reinforcing manner or in an asynchronous and mismatched manner. Specifically, this study is designed to address four interrelated tasks. First, it applies an allometric growth model to analyze the relative growth rates of forest ecological product value and farmers' livelihoods, us-

ing the allometric growth coefficient to determine whether the two systems exhibit coordinated symbiotic growth or asynchronous “misalignment.” Second, based on the Lotka–Volterra symbiotic model, it constructs a Bayesian hierarchical framework to estimate provincial-level symbiotic coefficients, identify specific symbiotic patterns, including mutualism, commensalism, competition and parasitism, and reveal their dynamic evolution across provinces and over time. Third, it employs a multi-period DID design to evaluate the causal effect of the 2017 Green Finance Reform and Innovation Pilot Policy on the forest–farmer symbiotic relationship, thereby examining whether external policy interventions strengthen or weaken ecological–livelihood synergy. Fourth, it introduces the LightGBM algorithm with SHAP value interpretation, in conjunction with symbiosis theory, to identify key variables associated with symbiotic equilibrium, such as financial development, technological progress and transportation infrastructure, as well as their regional heterogeneity.

This study is expected to make several contributions to the literature on forest ecological product value realization and farmers’ livelihoods. First, by introducing an allometric growth perspective, it moves beyond static correlation analysis and provides a dynamic approach to assessing whether ecological product value growth and livelihood improvement are synchronized. Second, by estimating symbiotic coefficients within a Bayesian hierarchical framework, it provides a systematic method for identifying the direction, intensity and dynamic evolution of the interaction between forest ecological product value and farmers’ livelihoods. Third, by incorporating a multi-period DID design, it aims to provide causal evidence on how green finance policy reshapes the ecological–livelihood linkage, addressing a methodological gap in existing studies that mainly rely on correlation analysis or average treatment effects. Fourth, by integrating LightGBM–SHAP with symbiosis theory, it seeks to identify regionally heterogeneous pathways through which external conditions shape forest–farmer symbiosis. These contributions also respond to prior findings that ecological compensation and sustainability policies do not automatically generate social or ecological benefits unless they are carefully designed. For example, Wu and Jin [24] show that different eco-compensation programs have heterogeneous effects across income groups, while Reale [41] emphasizes that ecosystem-service-based sustainability requires actions that restore or maintain the ecological functions on which economic activities depend. Building on these insights, this study further examines whether ecological product value realization and green finance can effectively support farmers’ livelihoods, rather than assuming that ecological product value growth will automatically translate into inclusive rural prosperity.

The remainder of this paper is organized as follows. Section 2 presents the materials, methods and data sources. Section 3 reports and discusses the empirical results, including the spatiotemporal evolution and allometric growth patterns, symbiotic coefficient estimation, policy evaluation and LightGBM–SHAP-based variable identification. Section 4 concludes the paper by summarizing the main findings, policy implications, limitations and future research directions.

2. Materials and Methods

This section presents the analytical framework, variable construction, model specifications and data sources. The empirical strategy is organized around four sequential questions. First, the allometric growth model is used to determine whether forest ecological product value and farmers’ livelihoods grow at synchronized or mismatched rates. Second, the Bayesian symbiotic coefficient model and the Lotka–Volterra interaction model are used to measure the intensity and direction of interactions between the two systems. Third, the multi-period DID model is used to identify the causal effect of the

green finance pilot policy on forest–farmer symbiosis. Finally, LightGBM-SHAP is used to explore the external conditions associated with symbiotic equilibrium and their regional heterogeneity. This stepwise design links growth mismatch, interaction patterns, policy effects and environmental drivers within a unified framework.

2.1. Analytical Framework and Model Specification

To address the four sequential research questions—(i) whether growth rhythms are synchronized, (ii) how the two systems interact directionally, (iii) whether green finance policy causally reshapes this relationship, and (iv) what environmental conditions enable symbiotic equilibrium—this study adopts a stepwise analytical framework. Each method is selected to answer one specific question, and their results are designed to complement one another: allometric growth analysis reveals the temporal mismatch in growth rates; the Lotka–Volterra model identifies the directional interaction pattern; the Bayesian hierarchical symbiotic coefficient quantifies the intensity and dynamic evolution of this interaction while filtering out short-term noise; the multi-period DID provides causal evidence on policy shocks; and LightGBM-SHAP explores nonlinear associations between external environmental variables and symbiotic equilibrium.

The analytical framework treats forest ecological product value and farmers' livelihoods as two symbiotic units embedded in a shared policy, market, technological, and resource environment. The framework clarifies how the two systems may develop through mutual reinforcement, one-way dependence, competition, or inhibition, and how this relationship can be evaluated through growth rhythm, interaction direction, policy shocks, and symbiotic-environment factors. Figures 1 and 2 summarize the symbiotic logic and evolutionary mechanism.

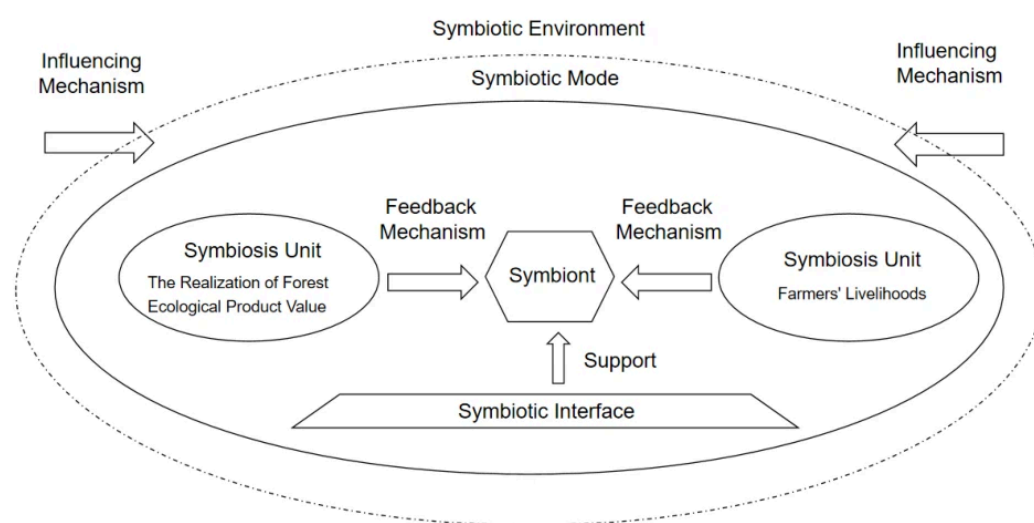


Figure 1. Symbiotic pattern diagram.

The analytical framework treats forest ecological product value and farmers' livelihoods as two symbiotic units embedded in a shared policy, market, technological, and resource environment. To prevent misinterpretation through a purely biological lens, Table A1 in Appendix A explicitly defines the ecological terms used herein and their specific operational meanings in the context of political economy, socio-forestry, and rural development policy.

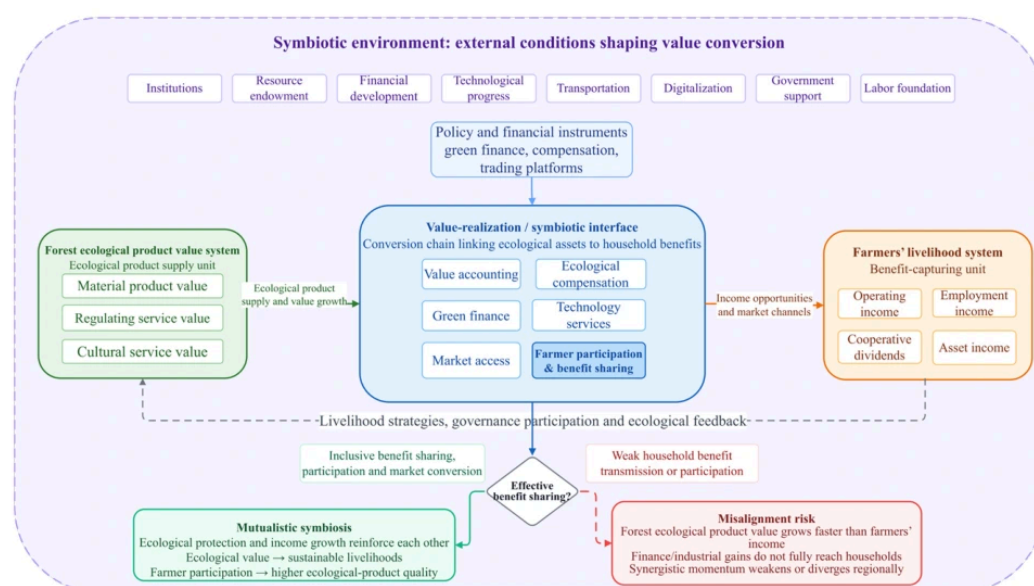


Figure 2. Evolutionary conceptual model.

2.1.1. Construction of the Forest Ecological Product Value Index

Based on the definitions in The Technical Guidelines on Gross Ecosystem Product, the total value of ecosystem products comprises the values of material products, regulating services, and cultural services [36]. Following the principles of scientific validity, systematicness, and data availability, and drawing on the conceptual framework of forest ecological products [42,43], this paper constructs an evaluation index system with three primary indicators: material product value, regulating service value, and cultural service value (Table 1).

Table 1. Evaluation index system of forest ecological product value.

Target Layer	First-Level Indicator	Second-Level Indicator	Measurement Indicator	Weight
Forest ecological product value	Material product value	Forestry output value	Total output value of the forestry industry	0.2276
			Input funds	0.2068
	Regulating service value	Ecological compensation	Government fiscal expenditure on agriculture, forestry, and water affairs	0.0862
			Species conservation	0.1474
	Cultural service value	Forestry tourism	Total output value of the tertiary forestry industry	0.3319

Material products represent direct use value and are measured by gross forestry output. Regulating service products, which are quasi-public goods (e.g., water conservation, air purification, soil retention), exhibit non-rivalry and non-excludability, making their property rights unclear; their value is thus proxied by government expenditure on agriculture, forestry, and water resources, and by total forestry investment. Species conservation is assessed using the protected-area method, with afforestation area serving as a proxy for nature reserve area.

Cultural service value is reflected in the rapid growth of characteristic economic forests, under-forest economy, and ecotourism, and is measured by forestry revenues and forest tourism income.

Since the data units differ, the entropy method is used to standardize indicators and calculate weights, thereby reducing subjective weighting bias (as shown in Table 1). The specific formulas are as follows:

$$X = (X^1, X^2, \dots, X^t)'_{nt \times m} = (x_{ij})_{nt \times m} \quad (1)$$

$$x'_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \quad (2)$$

$$y_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{nt} x'_{ij}} \quad (1 \leq i \leq nt, 1 \leq j \leq m) \quad (3)$$

$$e_j = -\frac{1}{\ln nt} \sum_{i=1}^{nt} y_{ij} \ln y_{ij} \quad (1 \leq i \leq nt, 1 \leq j \leq m) \quad (4)$$

$$d_j = (1 - e_j) \quad (5)$$

$$W_j = \frac{d_j}{\sum_{j=1}^m d_j} \quad (6)$$

where n denotes the number of study provinces, t denotes the number of years in the study period, and m denotes the number of evaluation indicators; x_{ij} is the original value of indicator j for sample i ; x'_{ij} is the range-standardized indicator value; y_{ij} is the value proportion of sample i under indicator j ; e_j is the information entropy of indicator j ; d_j is the information utility value; W_j is the objective weight of indicator j . The resulting weights are reported in Table 1.

Farmers' livelihoods are primarily proxied by net household operating income of rural residents [44]. This indicator captures income generated through household-based production and management activities—including forestry, crop cultivation, animal husbandry, and related services—and is therefore most directly related to farmers' ability to participate in and benefit from forest ecological product value realization. We acknowledge that this operationalization does not fully capture the multidimensional nature of livelihoods as conceptualized in the Sustainable Livelihoods Framework (SLA), which encompasses human capital, social capital, natural capital, physical capital, and financial capital [45]. Net operating income predominantly reflects the financial-capital and partial natural-capital dimensions, while dimensions such as social networks, human capital (education and skills), and physical assets (housing, equipment) are not explicitly measured. However, given that the central policy question of this study concerns whether forest ecological product value realization translates into tangible income benefits for rural households, net operating income serves as the most policy-relevant and directly measurable proxy. Furthermore, operating income is the livelihood component most sensitive to forest-based economic activities (e.g., non-timber forest products, understory economies, and ecological tourism), making it the appropriate focal indicator for analyzing the forest–farmer economic linkage.

2.1.2. Allometric Growth Model

The allometric growth model measures whether forest ecological product value and farmers' livelihoods grow at comparable rates. Vertical allometry captures temporal change within a province, whereas horizontal allometry captures cross-provincial differences in a given year. This two-dimensional design helps distinguish long-term evolutionary mismatch from spatial imbalance.

Vertical allometric growth relationship:

$$L_t = aF_t^b, \quad (7)$$

Horizontal allometric growth relationship:

$$L_i = aF_i^b, \quad (8)$$

In Equations (7) and (8), L denotes farmers' livelihood income, F denotes forest ecological product value, i denotes province, and t denotes year. The parameter a is a proportional coefficient, and b is the allometric growth coefficient. Following the classification criteria in Table 2, $b = 0.85$ indicates synchronized growth [46,47], $b > 0.85$ indicates faster growth in farmers' livelihood income, and $b < 0.85$ indicates faster growth in forest ecological product value.

Table 2. Classification criteria for allometric growth relationships.

	Grade	Classification Criterion	Type of Allometric Growth Relationship
Positive allometric growth	Positive allometric growth, Grade 3	$3 \leq b$	Strong farmers' income growth
	Positive allometric growth, Grade 2	$1 \leq b < 3$	Weak farmers' income growth
	Positive allometric growth, Grade 1	$0.85 \leq b < 1$	Coordination between forest ecological product value and farmers' income
Negative allometric growth	Negative allometric growth, Grade 1	$0.50 \leq b < 0.85$	Weak forest ecological product value growth
	Negative allometric growth, Grade 2	$0 \leq b < 0.50$	Strong forest ecological product value growth
	Negative allometric growth, Grade 3	$b < 0$	Contraction in forest ecological product value

2.1.3. Lotka–Volterra Symbiosis Model

The Lotka–Volterra (L–V) model, proposed in the 1920s, is a mathematical framework for two-species resource competition and has been widely applied beyond ecology. For instance, Lee et al. employed the L–V model to analyze the relationship between the Korea Stock Exchange (KSE) and the Korean Securities Dealers' Automated Quotations (KOSDAQ), as well as the dynamic effects of these two competing markets on the

Korean stock market [48]. Li Xuemin and colleagues, taking the grassland ecosystem and the pastoral economic system in Inner Mongolia as their research subjects, utilized the L-V model to characterize the dynamic interactive relationship between the two systems, and further explored their coupling symbiosis degree and spatiotemporal evolution characteristics [49]. The ecological–economic system investigated in this paper—comprising forest ecological product value and farmers’ livelihoods—shares general ecosystem attributes and exhibits interconnected, evolutionary traits similar to natural populations. Hence, analyzing their coupling mechanism via the L-V model is of substantial theoretical significance.

The Lotka–Volterra model is used to identify the interaction pattern between provincial forest ecological product value and farmers’ income. Depending on the signs and magnitudes of the interaction coefficients, the two systems can display mutualistic symbiosis, commensalism, competition, parasitism, amensalism, mutual inhibition, or no significant interaction.

$$\frac{dF_{it}}{dt} = r_F F_{it} \frac{K_F - F_{it} - \alpha L_{it}}{K_F}, \quad (9)$$

$$\frac{dL_{it}}{dt} = r_L L_{it} \frac{K_L - L_{it} - \beta F_{it}}{K_L}, \quad (10)$$

Let F_{it} denote forest ecological product value and L_{it} denote farmers’ livelihood income in province i and year t . K_F and K_L represent the environmental capacities (environmental capacity is the maximum load of pollutants that a given environment can accommodate without causing harm to human survival or natural ecosystems; in this paper, it represents the maximum values of K_F and K_L) of the forest ecological product value system and the farmers’ livelihood system, respectively, while r_F and r_L represent their endogenous growth rates. The interaction coefficients α and β measure the directional influence between the two systems under the sign convention in Equations (9) and (10).

Because this study uses provincial annual panel data from 2011 to 2022, continuous-time derivatives cannot be directly observed. Therefore, the L-V model is discretized before parameter estimation. This study uses one year as the time step ($\Delta t = 1$) and adopts the forward difference method to approximate continuous derivatives:

$$\frac{dF_{it}}{dt} \approx \frac{F_{i,t+1} - F_{it}}{\Delta t} = F_{i,t+1} - F_{it} = \Delta F_{it}, \quad (11)$$

$$\frac{dL_{it}}{dt} \approx \frac{L_{i,t+1} - L_{it}}{\Delta t} = L_{i,t+1} - L_{it} = \Delta L_{it}, \quad (12)$$

Accordingly, the continuous L-V model can be transformed into the following discrete difference form:

$$\Delta F_{it} = r_F F_{it} \frac{K_F - F_{it} - \alpha L_{it}}{K_F} + \varepsilon_{it}^F, \quad (13)$$

$$\Delta L_{it} = r_L L_{it} \frac{K_L - L_{it} - \beta F_{it}}{K_L} + \varepsilon_{it}^L, \quad (14)$$

The disturbance terms ε_{it}^F and ε_{it}^L capture unobserved shocks to the forest ecological product value system and the farmers’ income system, respectively. Before estimation, both variables are standardized to reduce dimensional differences, and environmental

capacities are set according to the sample maxima after standardization.

In terms of parameter estimation, this study uses the Bayesian MCMC method to estimate the interaction coefficients in the L-V model. Specifically, the system changes after discretization are assumed to follow a normal observation process:

$$\Delta F_{it} \sim N\left(r_F F_{it} \frac{K_F - F_{it} - \alpha L_{it}}{K_F}, \sigma_F^2\right), \quad (15)$$

$$\Delta L_{it} \sim N\left(r_L L_{it} \frac{K_L - L_{it} - \beta F_{it}}{K_L}, \sigma_L^2\right), \quad (16)$$

Here, σ_F^2 and σ_L^2 represent the variances of the two observation equations. To avoid the influence of overly strong prior assumptions on the estimation results, the following weakly informative priors are specified:

$$r_F, r_L \sim \text{HalfNormal}(1), \quad (17)$$

$$\alpha, \beta \sim N(0, 2^2), \quad (18)$$

$$\sigma_F, \sigma_L \sim \text{HalfNormal}(1), \quad (19)$$

Based on the above settings, this study obtains the posterior distributions of the interaction coefficients α and β through MCMC sampling. The symbiotic pattern between forest ecological product value and farmers' livelihood income is then identified according to the posterior means and signs of α and β under the sign convention in Equations (9) and (10).

2.1.4. Bayesian Symbiotic Coefficient

The traditional symbiotic coefficient is calculated from adjacent-year rates of change and can be sensitive to short-term fluctuations. To improve robustness, this study constructs a Bayesian hierarchical model that estimates latent rates of change while accounting for provincial heterogeneity and common annual shocks.

Let g_{it}^F and g_{it}^L denote the annual rates of change in forest ecological product value and farmers' livelihood income for province i in year t , respectively. These observed rates are modeled as noisy realizations of latent province-year growth tendencies, allowing the symbiotic coefficient to be estimated probabilistically rather than as a single deterministic ratio.

$$g_{it}^F \sim \mathcal{N}(\eta_{it}^F, \sigma_F^2), \quad (20)$$

$$g_{it}^L \sim \mathcal{N}(\eta_{it}^L, \sigma_L^2), \quad (21)$$

Here, η_{it}^F and η_{it}^L represent the latent mean rates of change of the two systems, while σ_F and σ_L represent the standard deviations of the two observation processes, respectively.

To control provincial heterogeneity and common annual shocks, the following hierarchical structure is specified:

$$\eta_{it}^F = \mu_F + \alpha_i^F + \gamma_t^F, \quad (22)$$

$$\eta_{it}^L = \mu_L + \alpha_i^L + \gamma_t^L, \quad (23)$$

Here, μ_F and μ_L represent the overall mean rates of change of the forest ecological product value system and the farmers' livelihood system, respectively; α_i^F and α_i^L represent province-level random effects; and γ_t^F and γ_t^L represent year-level random effects. The random effects are specified as follows:

$$\alpha_i^F \sim \mathcal{N}\left(0, \tau_{\alpha F}^2\right), \quad (24)$$

$$\alpha_i^L \sim \mathcal{N}\left(0, \tau_{\alpha L}^2\right), \quad (25)$$

$$\gamma_t^F \sim \mathcal{N}\left(0, \tau_{\gamma F}^2\right), \quad (26)$$

$$\gamma_t^L \sim \mathcal{N}\left(0, \tau_{\gamma L}^2\right), \quad (27)$$

Here, $\tau_{\alpha F}^2$, $\tau_{\alpha L}^2$ and $\tau_{\gamma F}^2$, $\tau_{\gamma L}^2$ are the variances of the province- and year-level random effects for the forest and livelihood systems, respectively.

The model adopts weakly informative priors:

$$\mu_F \sim \mathcal{N}\left(0, 0.5^2\right), \quad (28)$$

$$\mu_L \sim \mathcal{N}\left(0, 0.5^2\right), \quad (29)$$

$$\sigma_F, \sigma_L, \tau_{\alpha F}, \tau_{\alpha L}, \tau_{\gamma F}, \tau_{\gamma L} \sim \text{HalfNormal}(0.3), \quad (30)$$

In the Bayesian hierarchical model, the posterior latent rates η_{it}^F and η_{it}^L replace the observed rates g_{it}^F and g_{it}^L when calculating the bidirectional symbiotic ratios:

$$\delta_{it}^{FL} = \frac{\eta_{it}^F}{\eta_{it}^L}, \quad (31)$$

$$\delta_{it}^{LF} = \frac{\eta_{it}^L}{\eta_{it}^F}, \quad (32)$$

On this basis, the symbiotic coefficients are further obtained:

$$\theta_{it}^{F,B} = \frac{|\delta_{it}^{FL}|}{|\delta_{it}^{FL}| + |\delta_{it}^{LF}| + \epsilon}, \quad (33)$$

$$\theta_{it}^{L,B} = \frac{|\delta_{it}^{LF}|}{|\delta_{it}^{FL}| + |\delta_{it}^{LF}| + \epsilon}, \quad (34)$$

Here, ϵ is a small positive constant ($\epsilon = 10^{-8}$) used to avoid division by zero. The

coefficients $\theta_{it}^{F,B}$ and $\theta_{it}^{L,B}$ represent the relative interaction weights of the forest ecological product value system and the farmers' livelihood system in the posterior symbiotic structure, respectively. Because ε is extremely small, they approximately satisfy the following condition:

$$\theta_{it}^{F,B} + \theta_{it}^{L,B} = 1, \quad (35)$$

The Bayesian symbiotic equilibrium degree is further defined as follows:

$$B_{it}^B = 1 - \left| \theta_{it}^{F,B} - \theta_{it}^{L,B} \right|, \quad (36)$$

Here, B_{it}^B denotes the Bayesian bidirectional symbiotic equilibrium degree. A higher value indicates a more balanced contribution of forest ecological product value and farmers' livelihood income to the symbiotic relationship.

MCMC estimation and convergence diagnostics. The posterior distributions of all parameters were estimated using the No-U-Turn Sampler implemented in PyMC (V5). We ran four independent MCMC chains, each with 1000 warm-up (tuning) iterations and 1000 posterior draws, yielding a total of 4000 posterior samples. The target acceptance probability was set to 0.9 to ensure efficient exploration of the posterior space and to reduce the risk of divergent transitions. Convergence was assessed via the Gelman–Rubin $\widehat{R}$ statistic and visual inspection of trace plots. All $\widehat{R}$ values for the reported hyperparameters were close to 1.00 (well below the conventional threshold of 1.05), indicating good convergence across chains. The effective sample size was computed for each parameter to confirm that the posterior summaries were based on adequate independent information. Posterior uncertainty was quantified using 95% credible intervals (2.5th and 97.5th percentiles) for all derived quantities, including the provincial symbiotic coefficients $\theta_{it}^{F,B}$, $\theta_{it}^{L,B}$ and the equilibrium degree. All Bayesian computations were performed using PyMC and ArviZ. Full MCMC diagnostics, including summary statistics and trace plots, are available in Appendix A (Table A2 and Figure A1).

2.1.5. Difference-in-Differences Model

The difference-in-differences (DID) method is used to evaluate whether the 2017 green finance reform and innovation pilot policy changed the symbiotic relationship between forest ecological product value and farmers' livelihoods. The treatment group includes pilot provinces, while non-pilot provinces form the control group. Province and year fixed effects are included to control for time-invariant provincial characteristics and nationwide annual shocks.

$$B_{it} = \alpha_0 + \beta DID_{it} + \gamma Z_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (37)$$

In Equation (37), i denotes province and t denotes year. The dependent variable B_{it} represents the symbiotic coefficient. DID_{it} refers to the difference-in-differences estimator of the green finance pilot policy. Z_{it} is the set of province-level control variables, and γ is the corresponding coefficient vector. μ_i , λ_t and ε_{it} denote province fixed effects, year fixed effects, and random error term, respectively. The DID term captures the net policy effect after controlling for relevant variables. A negative coefficient indicates that the policy weakened ecological-livelihood synergy, whereas a positive coefficient indicates that it strengthened synergy.

2.1.6. LightGBM Model

The LightGBM-SHAP analysis is exclusively predictive and associative. It is used not as a substitute for causal inference but as a complementary tool to identify nonlinear statistical associations between symbiotic-environment variables and the predicted symbiotic equilibrium. SHAP values indicate which variables are important for model prediction, but they do not prove that a given variable actually causes changes in symbiotic equilibrium.

LightGBM is a gradient-boosting decision-tree algorithm designed for efficient nonlinear prediction. In this study, it is used not as a substitute for causal inference but as a complementary tool to identify nonlinear associations between the symbiotic environment and the symbiotic equilibrium degree.

The objective function of LightGBM includes a loss function and a regularization term. Its mathematical expression is as follows:

$$\mathcal{L} = \sum_{i=1}^n l(y_i, \hat{y}_i) + \sum_{k=1}^K \Omega(f_k), \quad (38)$$

In Equation (38), $\mathcal{L}$ is the overall objective function of LightGBM. n is the sample size. $l(y_i, \hat{y}_i)$ is the loss function, where y_i and $\hat{y}_i$ denote the true observed value and the model-predicted value of the i -th sample, respectively, and this term is used to measure the prediction error. K is the total number of decision trees generated during the iterations. $\Omega(f_k)$ is the regularization term, where f_k represents the k -th decision tree, and this term prevents overfitting by constraining the structural complexity of the tree.

2.1.7. SHAP Interpretation

SHAP values are used to interpret the LightGBM predictions by measuring the marginal contribution of each explanatory variable to the predicted symbiotic equilibrium degree. Positive SHAP values indicate that a variable increases the predicted equilibrium level, whereas negative values indicate that it lowers the predicted equilibrium level.

$$\phi_j = \sum_{S \subseteq F \setminus \{j\}} \frac{|S|!(p - |S| - 1)!}{p!} \left[f_{S \cup \{j\}}(x_{S \cup \{j\}}) - f_S(x_S) \right], \quad (39)$$

Equation (39) formulates the Shapley value ϕ_j for feature j , quantifying its average marginal contribution to the predicted symbiotic equilibrium degree across all possible feature coalitions. Here, F denotes the full feature set and $p = |F|$ represents the total number of features. $S \subseteq F \setminus \{j\}$ is an arbitrary subset that excludes feature j , with $|S|$ indicating its cardinality. The combinatorial weight derives from cooperative game theory, representing the probability that feature j joins coalition S in a uniformly random permutation of all p features, thereby ensuring a fair allocation of the total predicted value among individual variables. The term $f_{S \cup \{j\}}(x_{S \cup \{j\}}) - f_S(x_S)$ captures the incremental change in model prediction—i.e., the marginal contribution—when feature j is added to the subset S . By aggregating these marginal contributions over all possible subsets with their respective weights, ϕ_j yields a unique attribution that satisfies the four fundamental axioms of Efficiency, Symmetry, Dummy, and Additivity. Consequently, a positive ϕ_j indicates that feature j elevates the predicted symbiotic equilibrium level,

whereas a negative value implies that it reduces the predicted equilibrium level.

2.2. Data Collection

The empirical analysis uses balanced panel data for 31 Chinese provinces from 2011 to 2022, excluding Hong Kong, Macao, and Taiwan because of data comparability. The raw data, which are summarized in Table 3, are obtained from the China Statistical Yearbook, China Forestry and Grassland Yearbook, China Rural Statistical Yearbook, China Environmental Statistical Yearbook, provincial statistical yearbooks, and official statistical bulletins. Variables with inconsistent units are harmonized before estimation, and the entropy method and standardization procedures are applied as described above.

Table 3. Descriptive statistics.

VarName	Obs	Mean	SD	Min	Median	Max
Forest ecological product value	372	6.43×10^6	6.57×10^6	61,818.426	3.90×10^6	2.95×10^7
Farmers' livelihoods	372	4866.618	1872.042	833.400	4784.890	11,058.200
Financial development	372	3.478	1.136	1.678	3.227	7.605
Digitalization level	372	242.876	107.644	16.220	255.175	460.690
Total output value of the forestry industry	372	2.10×10^7	2.15×10^7	1.24×10^5	1.32×10^7	8.99×10^7
Total forestry investment	372	1.31×10^6	1.52×10^6	53,355	9.73×10^5	1.09×10^7
Government fiscal expenditure	372	573.499	285.091	91.780	535.905	1359.322
Afforestation area	372	2.02×10^5	1.63×10^5	35.485	1.71×10^5	8.05×10^5
Total output value of forestry tourism and leisure tourism	372	4.07×10^6	5.42×10^6	137.000	1.58×10^6	2.33×10^7
Forest coverage rate	372	32.835	18.068	4.020	35.840	66.800
Environmental protection expenditure	372	149.722	99.472	16.050	126.090	747.440
Per capita GDP	372	60,085.694	30,288.118	16,413.000	52,242.500	1.90×10^5
Transportation conditions	372	1.44×10^5	98,924.206	1027.629	1.41×10^5	4.34×10^5
Urbanization level	372	59.167	12.989	22.810	58.340	89.600
Labor foundation	372	41,099.804	65,821.570	496.000	23,788.000	4.51×10^5
Technological progress	372	0.871	0.384	0.325	0.802	1.849

The China Statistical Yearbook (2011–2022) offers strong official authority, full provincial coverage, unified standards, and high accessibility, providing a solid macro-level panel dataset for 31 provinces. However, limitations persist: indicator caliber changes over the long period complicate cross-temporal matching; data granularity is coarse, with insufficient coverage for segmented forestry sectors; missing values for certain province-year observations are filled via linear interpolation to maintain a balanced panel; and regional heterogeneity in statistical precision may affect robustness.

3. Results and Discussion

This section reports and interprets the empirical results in four steps. We first examine the spatiotemporal evolution of forest ecological product value and farmers' livelihoods and identify their allometric growth patterns. We then estimate provincial symbiotic coefficients and classify the interaction patterns between the two systems. Next, we evaluate whether the green finance pilot policy changed the forest–farmer symbiotic relationship. Finally, we use LightGBM-SHAP to identify the external conditions associated with symbiotic equilibrium. Rather than treating these results as separate exercises, the discussion focuses on how ecological value growth is, or is not, transformed into

livelihood benefits under different regional and policy conditions.

3.1. Development Status

From 2011 to 2022, both forest ecological product value and farmers' income increased substantially. Mean provincial forest ecological product value rose from RMB 27.443 billion in 2011 to RMB 91.869 billion in 2022, while farmers' income also grew steadily. However, the spatial trajectories of the two systems were not synchronized. High-income areas expanded from the eastern coastal region toward inland provinces, whereas high forest ecological product value became increasingly concentrated in the Yangtze River Basin and Southwest China.

As shown in Figures 3 and 4, the spatial distribution of farmers' income shifted significantly across the study period. Spatial visualization further indicates that ecological-product growth and income growth followed different regional logics. This divergence suggests that ecological resource advantages alone are insufficient to generate livelihood gains unless institutional, market, and participation mechanisms transmit ecological value to households.

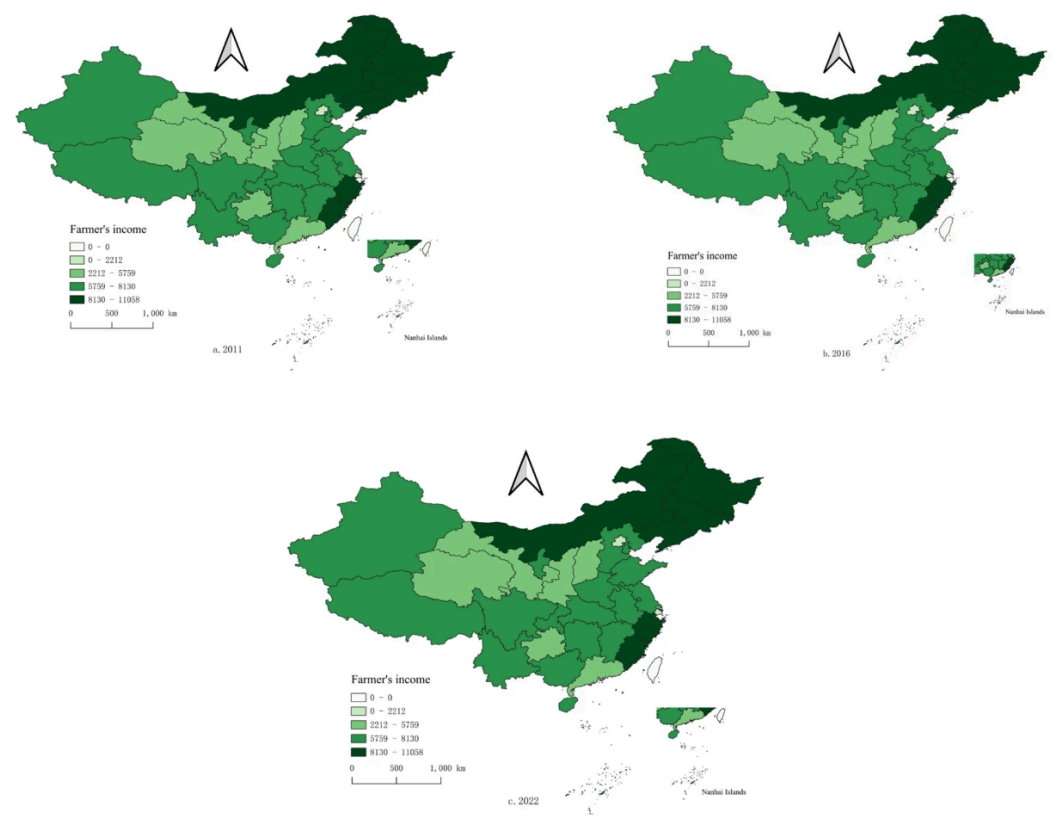


Figure 3. Spatial changes in farmers' income.

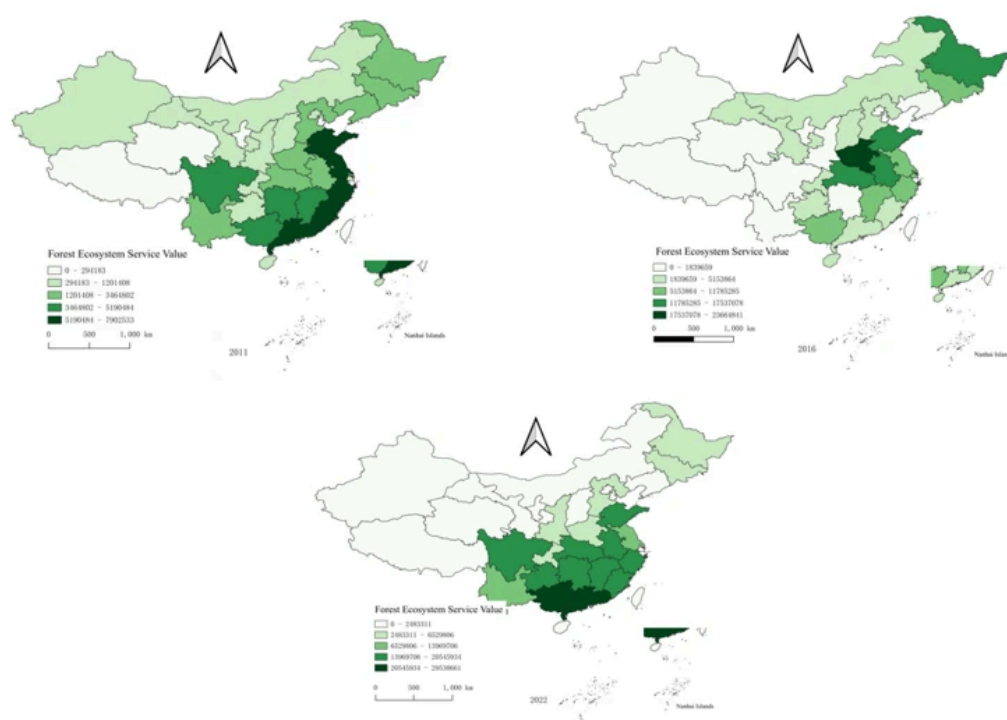


Figure 4. Spatial changes in forest ecological product value.

3.2. Allometric Growth Analysis

The allometric results reveal a clear mismatch between the growth of forest ecological product value and farmers' income. At the national scale, 87% of provinces were classified as negative allometric growth, meaning that forest ecological product value grew faster than farmers' income. This finding suggests that forest ecological product value realization has expanded more rapidly than the mechanisms through which farmers capture livelihood benefits.

A staged comparison between 2011–2016 and 2017–2022 shows that the allometric pattern changed markedly after 2017. As illustrated in Figure 5, several provinces shifted to different allometric grades between the two periods, indicating that the ecological-livelihood relationship was sensitive to policy, market, and regional development conditions during the later period.

From a symbiosis-theory perspective, negative allometry indicates that the ecological unit and the livelihood unit did not evolve at the same pace. Such a pattern may improve ecological-product supply while leaving household benefits behind, thereby creating a structural risk: ecological value may be accumulated, but its livelihood conversion efficiency may remain insufficient.

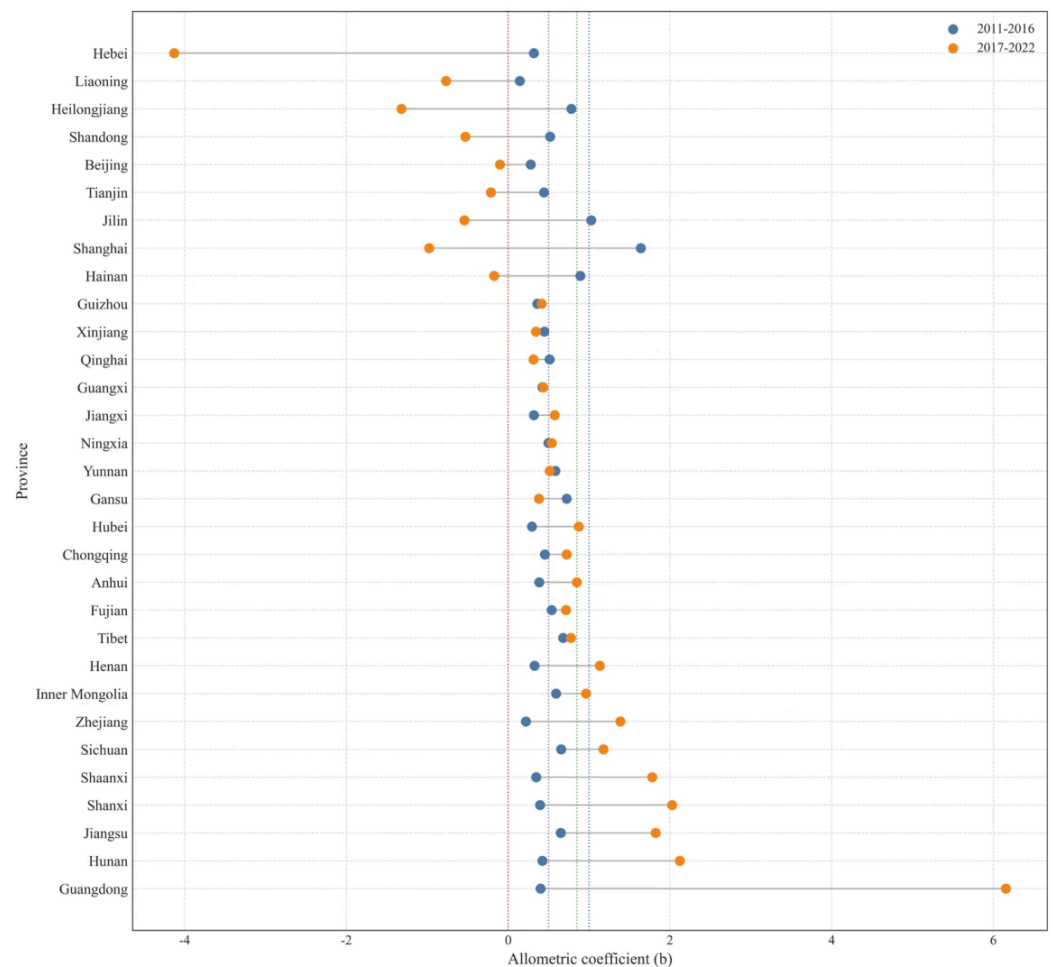


Figure 5. Provincial allometric growth coefficients by stage.

3.3. Symbiotic Coefficient Analysis

The estimated symbiotic coefficients indicate that most provinces maintained medium-to-high ecological-livelihood synergy during 2012–2022. As shown in Figure 6, the national symbiotic coefficient increased before 2019 but declined thereafter. Guangdong, Guangxi, Jiangxi, Zhejiang, and Hubei remained at high levels for relatively long periods, whereas some western and northeastern provinces displayed weaker synergy. Nationally, the symbiotic coefficient increased before 2019 and then declined, showing that the momentum of coordinated ecological-livelihood development weakened after the peak period.

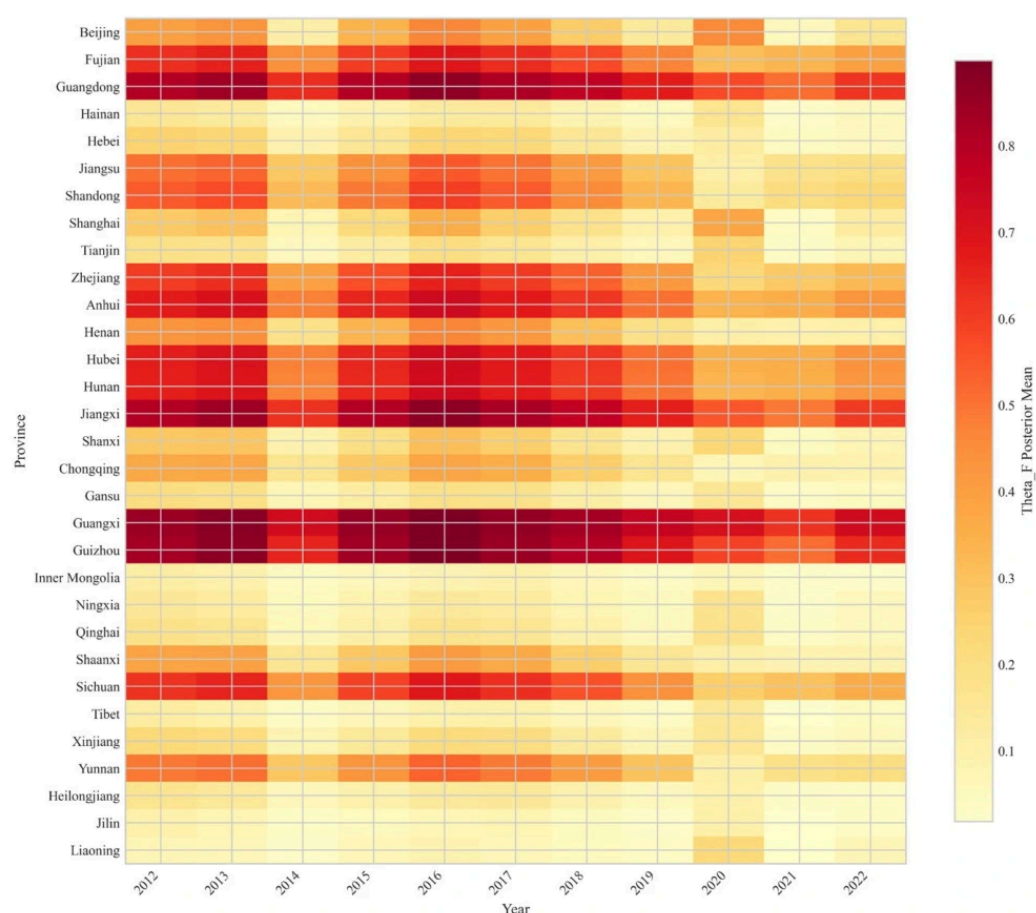


Figure 6. Symbiotic coefficient between forest ecological product value and farmers' livelihoods.

Kernel density estimates confirm this dynamic pattern. Figure 7 presents the kernel density estimates, showing that the distribution first converged and then diverged. The national distribution first became more concentrated, suggesting convergence in symbiotic development, but later widened, indicating renewed divergence among provinces. This change implies that the mechanisms linking forest ecological product value to farmers' livelihoods became less stable across regions.

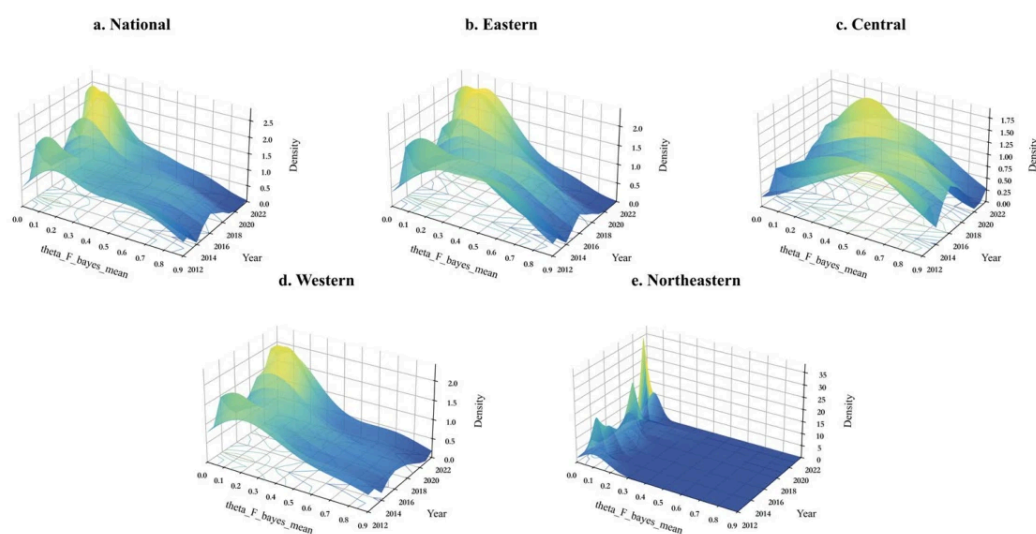


Figure 7. Kernel density estimation of symbiotic coefficients nationwide and in the four major regions.

3.4. Causal Inference Using the Difference-in-Differences Model

Estimated symbiosis coefficients show that the symbiosis level between forest ecological product value realization and farmers' income peaked in 2016 but dropped sharply in 2017. This short-term fluctuation cannot be explained by routine factors (e.g., production cycles, prices, or income changes), suggesting exogenous policy shocks may have disrupted their co-evolution. Given China's 2017 green finance reform pilot, this policy likely altered funding sources and operator structures for ecological value realization, redistributed value-added benefits, and thus structurally impacted the symbiosis. We therefore hypothesize that the pilot policy weakens the symbiotic evolution between forest ecological product value realization and farmers' income. To identify its net causal effect, we subsequently employ a difference-in-differences (DID) model.

3.4.1. Baseline Regression Results

As shown in Table 4, the multi-period DID estimates from Models 1 and 2 indicate that the 2017 green finance pilot policy had a statistically significant negative effect on the symbiosis coefficient. Model 1, which excludes control variables, yields a coefficient of -0.033 ($p = 0.025$), while Model 2, which adds controls for digitalization and financial development to mitigate omitted variable bias, gives -0.023 ($p = 0.099$). This result suggests that the pilot policy may have strengthened ecological finance and green investment while weakening, at least in the short run, the direct conversion of forest ecological product value into farmers' livelihood benefits.

Table 4. Baseline regression results.

VARIABLES	(1)	(2)
	Model 1	Model 2
DID	-0.033^{**}	-0.023^{*}
	(-2.25)	(-1.65)
Cv1		-0.003^{***}
		(-4.75)
Cv2		-0.006
		(-0.48)
Constant	0.323^{***}	1.158^{***}
	(85.04)	(6.51)
Observations	341	341
R-squared	0.943	0.950
Province FE	YES	YES
Year FE	YES	YES
Within R-sq	0.0101	0.132

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

3.4.2. Pre-Policy Parallel Trend Test

The event-study parallel-trend test uses 2016 as the benchmark year. As shown in Figure 8, the pre-policy coefficients are not statistically significant, supporting the comparability of treatment and control provinces before the pilot policy and strengthening the credibility of the DID identification strategy. After the policy implementation, although the estimated coefficient for 2018 has not yet reached statistical significance, the pronounced downward trend indicates that the weakening impact of the green finance pilot policy exhibits a gradually unfolding time-lag feature. Such a lag may be attributed

to the fact that policy transmission, enterprise transformation, and market adjustment all require a certain period to materialize.

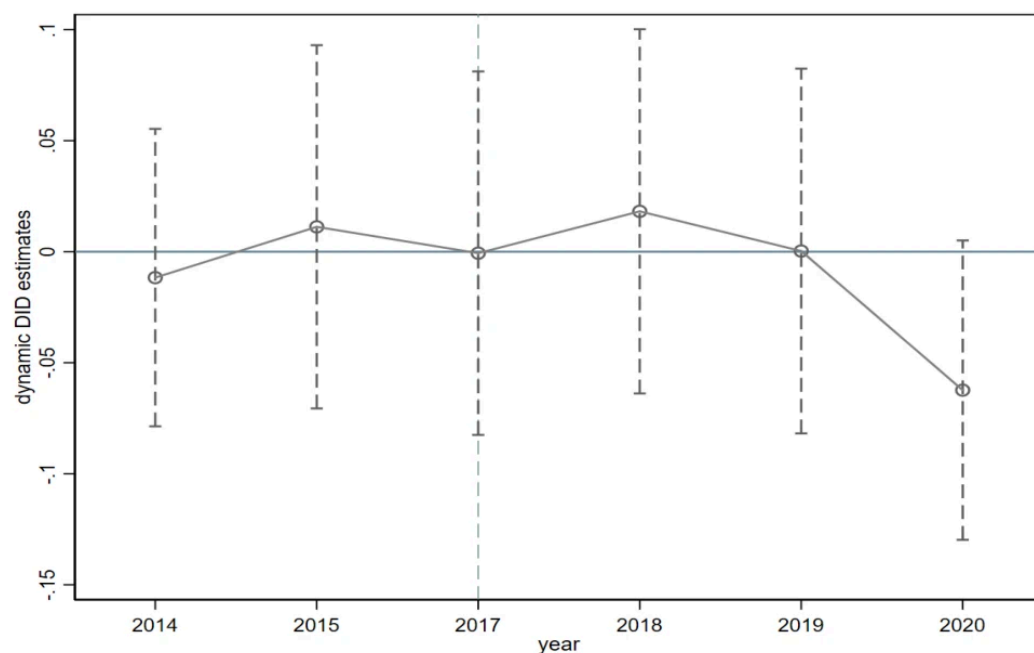


Figure 8. Parallel trend test.

3.4.3. Placebo Test

The placebo test randomly assigns pilot status to provinces and re-estimates the DID model repeatedly. Figure 9 shows that the placebo coefficients are centered around zero, distinct from the actual estimate, indicating that the observed policy effect is unlikely to be driven by random assignment or accidental trends.

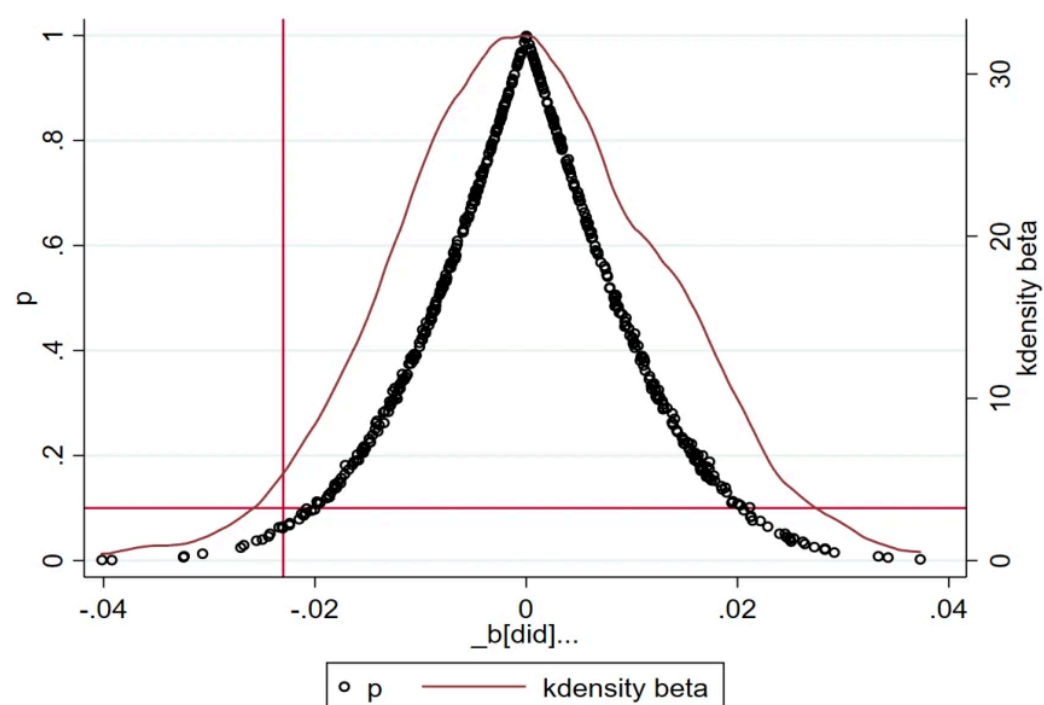


Figure 9. Placebo test results.

3.4.4. Robustness Test

To ensure robustness and avoid sample selection bias, we conduct two checks. First, we apply PSM-DID: propensity scores are estimated via a Logit model, and treatment/control groups are formed using 1:1 nearest-neighbor matching. The result (column 1, Table 5) yields a negative significant DID coefficient ($\beta = -0.0276$, $p = 0.069$), confirming robustness. Second, given that Yunnan and Sichuan introduced concurrent policies in 2017 (e.g., collective forest tenure reform and ecological compensation) that may confound the net policy effect, we exclude these provinces. The result (column 2, Table 5) remains negative and significant ($\beta = -0.029$, $p = 0.048$), further supporting robustness.

Table 5. Robustness test results.

VARIABLES	(1)	(2)
	Model 1	Model 2
DID	−0.0276 *	−0.029 **
	(−1.9032)	(−1.98)
Cv1	−0.0042 ***	−0.003 ***
	(−4.5656)	(−5.13)
Cv2	0.0944 **	−0.018
	(2.3747)	(−1.46)
Constant	1.1664 ***	1.249 ***
	(4.8872)	(7.14)
Observations	90	319
R-squared	0.989	0.954
Province FE	YES	YES
Year FE	YES	YES

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

3.5. Symbiotic Pattern Analysis

The L-V model identifies substantial spatial heterogeneity in symbiotic patterns. Although mutualistic symbiosis dominates at the national scale, regional patterns differ. As illustrated in Figure 10, the eastern region is mainly characterized by mutualistic symbiosis, the central region shows stronger one-way dependence, and the western and northeastern regions display more competitive or mutually inhibiting relationships. These results imply that a unified national policy may be insufficient. Region-specific mechanisms are needed to improve ecological-livelihood synergy.

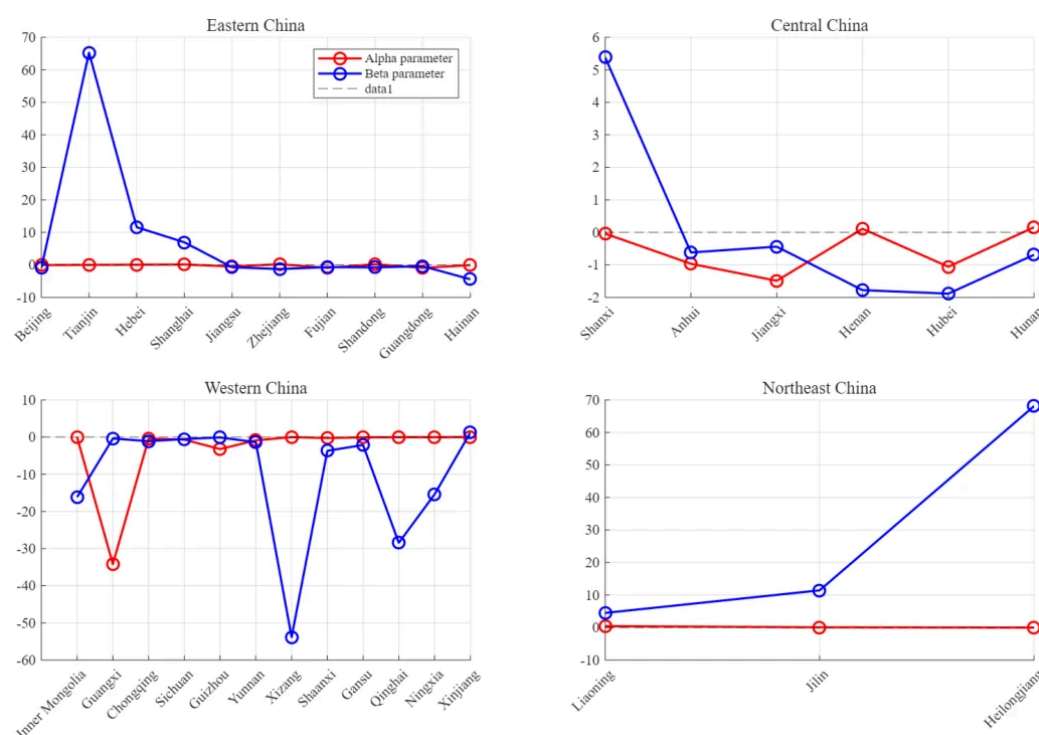


Figure 10. Alpha and beta Values of the L-V model in different regions.

3.6. Drivers of Symbiotic Equilibrium

3.6.1. SHAP-Based Interpretation of Symbiotic-Environment Variables

After estimating symbiotic relationships, this section examines which symbiotic-environment variables are most strongly associated with equilibrium between forest ecological product value and farmers' livelihoods. This analysis complements the DID results by identifying potential enabling conditions rather than causal policy effects.

3.6.2. Model Comparison and Selection

To reduce dependence on a single prediction model, five machine-learning models are compared: SVR, Random Forest, CatBoost, XGBoost, and LightGBM. As shown in Figure 11, model performance is assessed using R^2 , MAE, MSE, RMSE, and MAPE, and LightGBM is selected because it provides the best overall balance between predictive accuracy and stability.

Higher R^2 values indicate stronger predictive performance, while lower MAE, MSE, RMSE, and MAPE values indicate smaller prediction errors. The comparison is used only for selecting the most suitable predictive model for SHAP interpretation, not for replacing the causal DID analysis.

During actual training, LightGBM improves training efficiency through histogram-based feature splitting and a leaf-wise growth strategy, and controls overfitting risks through learning rate, tree depth, number of leaves, subsample ratio, and regularization parameters. The results show that when symbiotic equilibrium degree is used as the dependent variable, all five machine learning models have generally good predictive performance. Among them, CatBoost has the highest test-set R^2 , at 0.7408. LightGBM has a test-set R^2 of 0.7394, which is basically close to that of CatBoost. At the same time, the MAE and MAPE of LightGBM are 0.0901 and 0.4671, respectively, both lower than those of CatBoost, indicating better performance in controlling average error. Considering predictive accuracy, error level, model efficiency, and the convenience of subsequent SHAP

interpretation, this study selects LightGBM as the baseline model for analyzing the association mechanisms of the symbiotic environment.

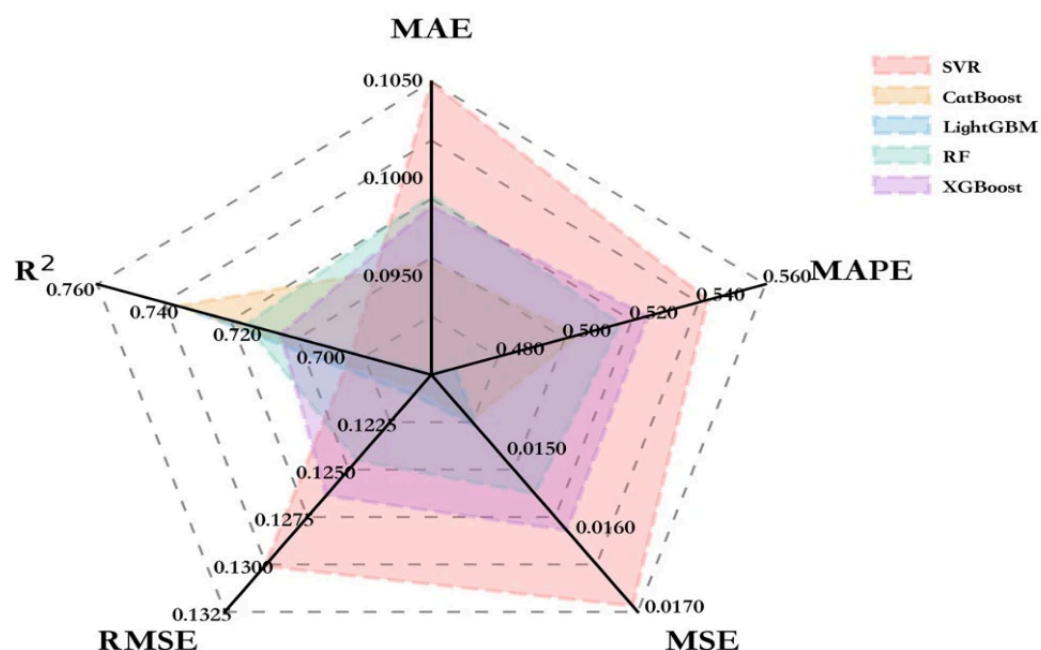


Figure 11. Radar chart for model comparison.

3.6.3. Selection of Symbiotic-Environment Variables

Variable selection follows three principles. First, explanatory variables should not overlap with the indicators used to construct the symbiotic coefficient, thereby reducing mechanical correlation. Second, variables should reflect the symbiotic environment identified in the theoretical framework. Third, the variables should be available consistently across provinces and years.

Accordingly, as summarized in Table 6 below, this study selects the following symbiotic environmental variables as model explanatory variables:

Table 6. Symbiotic environmental variables.

Variable Code	Variable Name	Variable Meaning	Definition	Unit	Data Source
X1	Ecological resource endowment	Reflects the forest resource base and ecological product supply conditions	Provincial forest coverage rate	%	China Statistical Yearbook
X2	Government support	Reflects the degree of government support for ecological protection, environmental governance, and public investment	Total fiscal expenditure on environmental protection	100 million RMB	China Statistical Yearbook
X3	Economic foundation	Reflects the level of regional economic	Per capita Gross Domestic Product (GDP)	RMB/person	China Statistical Yearbook

Variable Code	Variable Name	Variable Meaning	Definition	Unit	Data Source
		development and consumption carrying capacity			
X4	Transportation conditions	Reflects regional logistics, factor mobility, and market connectivity	Total freight traffic (all modes)	10,000 tons	China Statistical Yearbook; China Transport Statistical Yearbook
X5	Digitalization level	Reflects the development level of digital finance, digital platforms, and informatization	Peking University Digital Inclusive Finance Index	Index value (dimensionless)	Institute of Digital Finance
X6	Urbanization level	Reflects urban–rural factor mobility and the stage of regional development	Share of urban permanent residents in total population	%	China Statistical Yearbook
X7	Labor foundation	Reflects forestry-related labor and farmers' participation capacity	Year-end number of employees in the forestry system	Persons	China Statistical Yearbook
X8	Financial development	Reflects regional financial-resource allocation capacity	(Total deposits + Total loans of financial institutions)/Regional GDP	Ratio (dimensionless)	China Statistical Yearbook
X9	Technological progress	Reflects agricultural mechanization, production efficiency, and technical support capacity	Total power of agricultural machinery/Cultivated land area × 1000	10,000 kW/1000 ha	China Statistical Yearbook

Before model training, variance inflation factors (VIFs) are calculated to examine multicollinearity. Figure 12 reports the VIF values for all selected symbiotic-environment variables. The VIF results indicate that all variables fall within an acceptable range, suggesting that the selected symbiotic-environment variables can be jointly included in the LightGBM model.

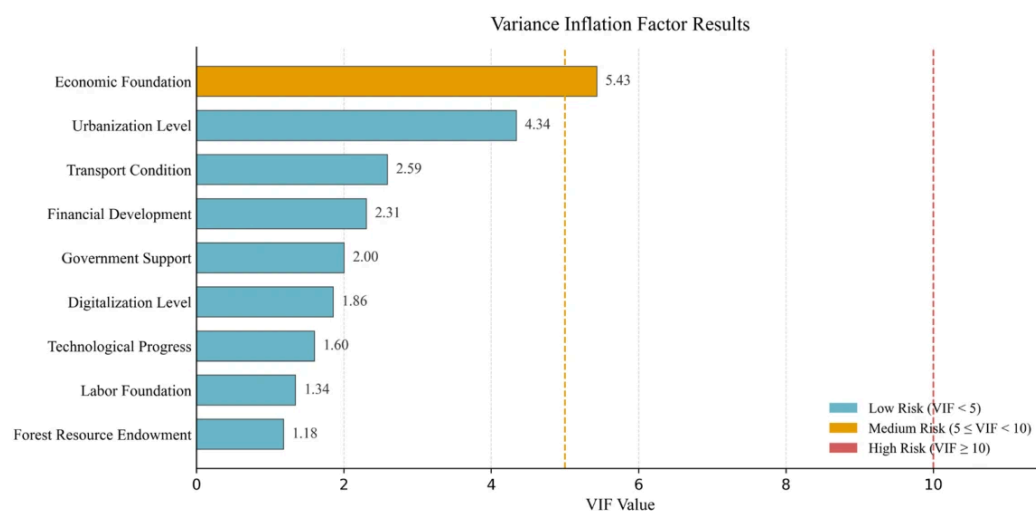


Figure 12. VIF test results.

3.6.4. Single-Variable SHAP Analysis

Based on the LightGBM model, SHAP values are used to identify how strongly each symbiotic-environment variable is associated with the predicted symbiotic equilibrium degree.

At the national level, financial development, technological progress, and transportation conditions exhibit the highest predictive importance for symbiotic equilibrium. These variables are commonly hypothesized as potential channels through which forest ecological product value may be linked to market opportunities, technical capacity, and household income (see Figures 13 and 14).

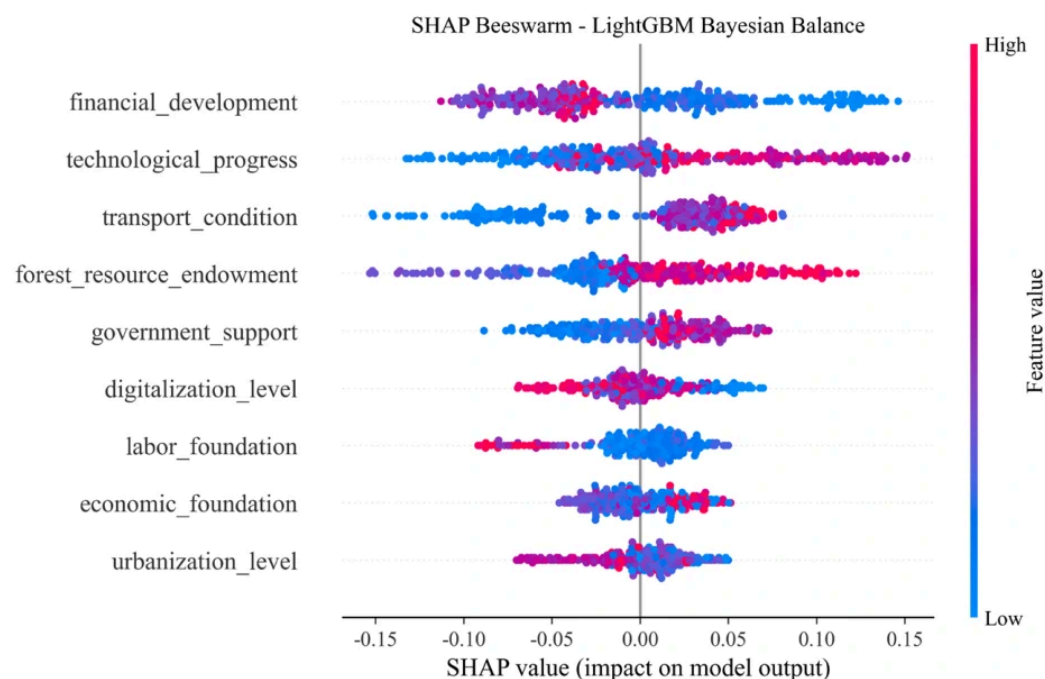


Figure 13. Nationwide variable detection results.

Regional results show that the eastern region displays the strongest predictive associations with financial development, transportation conditions, and labor foundations. This pattern is consistent with a relatively mature market environment in which ecological product value realization is statistically linked to finance-market linkages and farm-

ers' capacity to participate in value chains (see Figure 15).

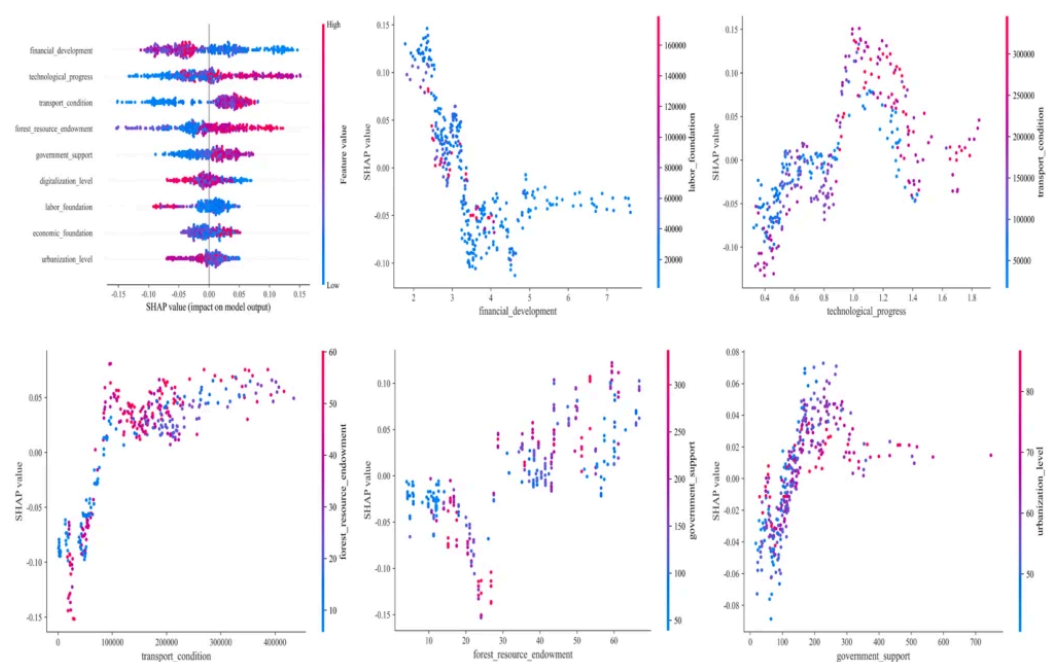


Figure 14. Variable beeswarm diagram.

In the central region, ecological resource endowment and technological progress show higher predictive importance. This suggests that the transformation of forest resources into income depends on processing capacity, technical services, and market connectivity.

In the western region, ecological resource endowment exhibits high predictive importance, but resource advantages co-occur with policy support, labor participation, and market access to become livelihood benefits. Without these enabling conditions, ecological value may remain weakly connected to household income.

In the northeastern region, financial development and transportation conditions show particularly high predictive importance. This finding suggests that revitalizing forest ecological product value requires stronger industrial conversion capacity and better connections between ecological resources and external markets.

Overall, the SHAP results suggest that symbiotic equilibrium is not determined by resource endowment alone. It depends on the combined influence of finance, technology, infrastructure, policy support, labor participation, and regional economic foundations.

3.6.5. Bivariate SHAP Interaction Associations

On the basis of single-variable SHAP analysis, SHAP interaction values are calculated to examine whether pairs of variables jointly shape symbiotic equilibrium. This step helps identify compound mechanisms that cannot be captured by main effects alone.

Figure 16 shows the interaction associations results of symbiotic environmental variables at the national level and in the four major regions. Nationally, the predictive interaction between transportation conditions and technological progress is the most prominent. Interactions between ecological resource endowment and technology, and between finance and market-support variables, also contribute to symbiotic equilibrium, indicating that infrastructure and technology jointly affect the conversion of ecological

value into livelihoods.

In the eastern region, joint predictive associations are mainly observed between ecological resource endowment and financial development, and between ecological resource endowment and digitalization level. In addition, combinations such as transportation conditions and labor foundation, and transportation conditions and financial development, also show strong associations. This indicates that the realization of forest ecological product value in the eastern region depends more on the joint effects of resource base and financial, digital, transportation, and labor variables.

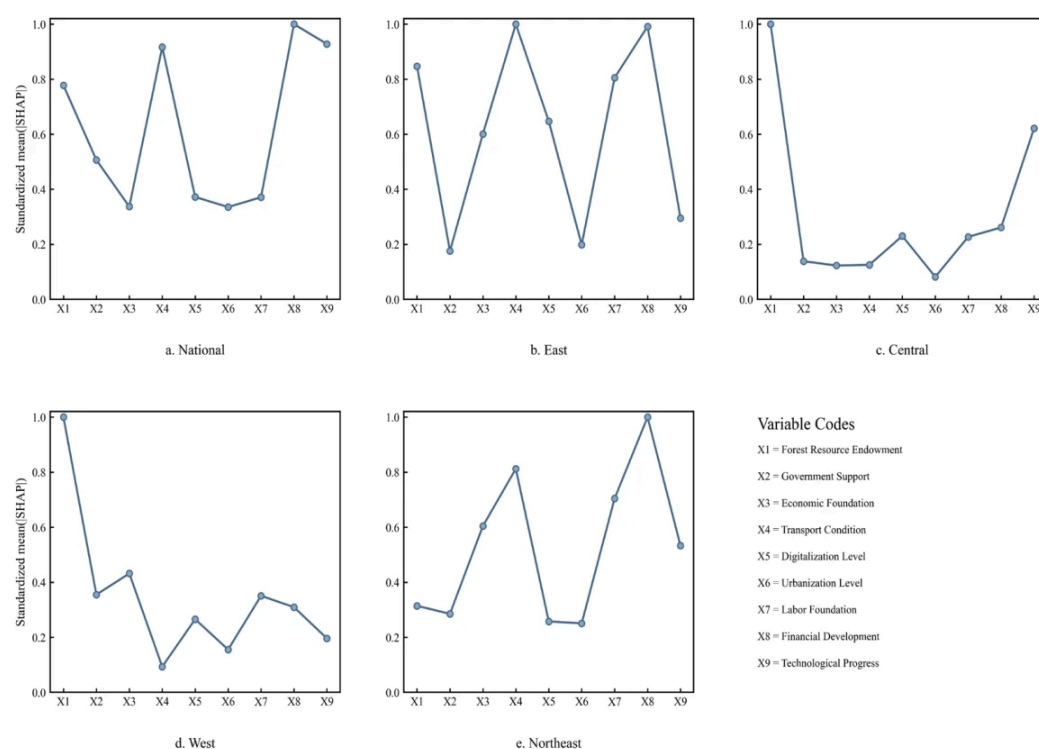


Figure 15. Detection results nationwide and across regions.

In the central region, interaction associations are concentrated between ecological resource endowment and transportation conditions, labor foundation, and technological progress. Among these, the interaction between ecological resource endowment and transportation conditions is the most prominent, indicating that the key to transforming forest ecological product value into farmers' livelihood benefits in the central region lies in whether the resource base can achieve market connection through transportation networks. The central region connects east and west as well as north and south, and improvements in transportation conditions can enhance the external accessibility of forest ecological products, understory products, and ecological tourism resources, expanding the market radius. At the same time, the interactions between ecological resource endowment and labor foundation and technological progress also indicate that ecological resources can more effectively generate stable livelihood benefits only when combined with farmers' participation capacity and technological improvement.

In the western region, the predictive interaction is most prominent for the combination of ecological resource endowment and labor foundation. Combinations such as government support and economic foundation, ecological resource endowment and technological progress, labor foundation and financial development, and urbanization level and labor foundation also show strong synergy. This suggests that the symbiotic relationship between forest ecological product value and farmers' livelihoods in the western

region shows a stronger predictive association with the combination of resource base and farmers' participation capacity. The western region is rich in ecological resources, but its market-oriented conversion capacity and industrial foundation are relatively weak. Whether ecological resources can be transformed into farmers' livelihood benefits therefore depends critically on whether farmers can participate in ecological management and protection, the understory economy, forest tourism, ecological product operations, and related service activities.

The interaction matrix for the northeastern region shows that no clearly dominant bivariate predictive interaction is formed among the variables, and prediction of symbiotic equilibrium level relies more on the main effects of several basic variables. This result indicates that the symbiotic mechanism between forest ecological product value and farmers' livelihoods in Northeast China may not yet have formed a stable multivariable synergistic structure, but instead mainly reflects separate support from basic conditions. Considering the small number of provinces in Northeast China and the relatively limited sample size, the interaction effects require further verification using finer-scale data.

Combining the single-variable and bivariate results shows that ecological-livelihood synergy is statistically associated with compound mechanisms rather than by a single variable. Policies that improve only ecological resources or only financial supply may have limited effects unless they are linked with technology, market access, and farmers' participation.

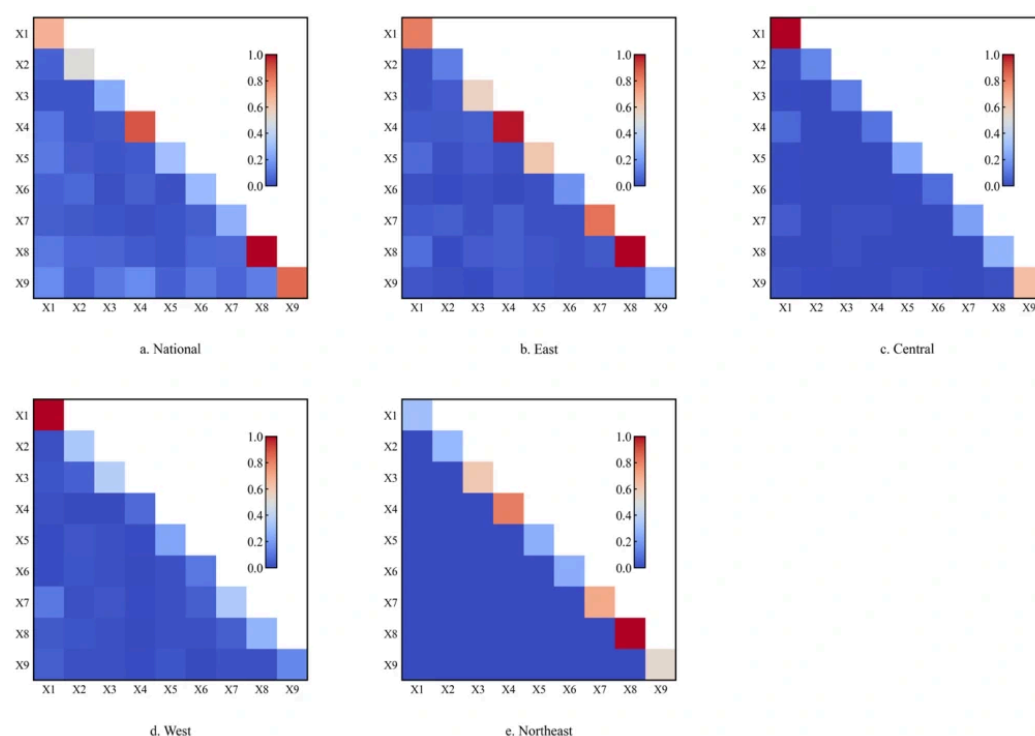


Figure 16. Interaction variable detection results nationwide and across regions.

3.7. Discussion

3.7.1. Allometric Growth Mismatch and the Decoupling of Ecological and Livelihood Gains

The finding that 87% of Chinese provinces exhibited negative allometric growth between 2011 and 2022 provides large-sample, province-level evidence for a proposition that has long been suggested by the conservation–livelihood literature: ecological value growth does not automatically translate into synchronous welfare gains for local house-

holds. While forests and other natural resources are widely documented as substantial contributors to rural livelihoods—particularly in forest-dependent and low-income communities—our results indicate that the rate of forest ecological product value expansion has systematically outpaced the rate of farmers’ operating income growth. This temporal mismatch, or “misalignment,” implies that the institutional and market mechanisms required to channel ecological surplus into household income remain underdeveloped relative to the speed of ecological asset accumulation.

This decoupling is consistent with the broader empirical record on payments for ecosystem services (PES) and eco-compensation programs in China. Le & Leshan and Li et al. demonstrate that ecological protection policies can support poverty reduction, yet their welfare impacts are highly heterogeneous across regions, projects, and income groups. Our allometric growth coefficient extends this line of inquiry by moving beyond static correlation or average treatment effects to capture the dynamic rhythm of co-evolution. When $b < 0.85$, forest ecological product value and farmers’ livelihoods are effectively on divergent growth trajectories—a pattern that static regressions might overlook if both variables are simply trending upward. In this respect, the allometric framework offers a diagnostic tool that is sensitive to the relative velocity of ecological and economic change, thereby complementing the existing literature’s focus on levels and gaps.

3.7.2. Symbiotic Patterns and the Co-Evolutionary Framework

The Bayesian hierarchical symbiotic coefficient and the Lotka–Volterra (L–V) interaction model reveal that the relationship between forest ecological product value and farmers’ livelihoods is not a simple linear linkage but a coupled socio-ecological interaction that varies in both direction and intensity across provinces and over time. Cao et al. recently adopted a symbiotic perspective to assess China’s ecological–economic relationship at the macro level; however, their analysis remained largely confined to aggregate ecosystem services and regional GDP. By contrast, this study operationalizes symbiosis theory at the forest–farmer interface, employing a Bayesian hierarchical framework to estimate latent growth rates while controlling for provincial heterogeneity and common annual shocks. This methodological choice is particularly important because traditional deterministic symbiotic coefficients, calculated from adjacent-year rates of change, are sensitive to short-term fluctuations and extreme values. The Bayesian approach smooths these transitory shocks through latent variables, yielding more robust estimates of long-term co-evolutionary tendencies.

The L–V model further identifies substantial spatial heterogeneity in symbiotic patterns. Mutualistic symbiosis dominates in the eastern region, where market infrastructure, financial depth, and technological capacity appear to facilitate reciprocal reinforcement between ecological value and livelihood income. The central region exhibits stronger one-way dependence, suggesting that farmers’ livelihoods benefit from forest ecological products but contribute less to ecological value in return. Western and north-eastern provinces, by contrast, display more competitive or mutually inhibiting relationships, echoing the findings of Liu & Kontoleon and Wang et al. that PES programs in less-developed regions often confront higher opportunity costs, weaker market access, and limited participation channels.

3.7.3. Green Finance Policy and the Transmission Mechanism to Livelihoods

The multi-period difference-in-differences results indicate that the 2017 Green Finance Reform and Innovation Pilot Policy significantly weakened the forest–farmer symbiotic relationship in pilot provinces. At first glance, this negative causal effect appears to contradict recent studies by Wu et al. and Xu et al., who find that green finance

policies promote forest ecological product value realization and environmental improvement. However, this apparent contradiction is reconciled by distinguishing between ecological value growth and improvements in farmers' livelihoods. Green finance instruments—such as green bonds, carbon-sink finance, and ecological collateral loans—may indeed channel capital toward ecological protection and green industries, yet the initial beneficiaries of these financial flows are often large enterprises, state-owned forest farms, or platform-based operators rather than smallholder farmers.

This interpretation is reinforced by the event-study parallel-trend test (Figure 8), which shows that the negative policy effect unfolds gradually after 2017 rather than appearing instantaneously. Such a time lag is consistent with the institutional reality that policy transmission, enterprise transformation, and market adjustment require several years to materialize. It also resonates with Diao et al., who argue that hybrid ecological compensation mechanisms are needed to enhance livelihood resilience; purely finance-oriented ecological policy, without explicit benefit-sharing requirements or farmer-accessible credit products, may inadvertently prioritize ecological investment and industrial upgrading over household welfare. Consequently, the negative DID effect should not be interpreted as evidence against green finance per se, but rather as a warning that finance-led ecological policy must be carefully designed to include cooperative participation mechanisms, profit-sharing arrangements, and monitoring indicators for rural household income and employment.

Consequently, the negative DID effect should not be interpreted as evidence against green finance per se, but rather as a warning that finance-led ecological policy must be carefully designed to ensure that ecological value growth is translated into accessible, equitable, and locally embedded income channels for farmers. The weakening of the symbiotic relationship reflects not a failure of green finance to improve ecological outcomes, but a failure of the pilot design to ensure that the resulting ecological surplus is effectively transmitted to farmers.

3.7.4. Regional Heterogeneity and Symbiotic-Environment Drivers

The LightGBM-SHAP analysis identifies financial development, technological progress, and transportation infrastructure as the most important symbiotic-environment variables associated with equilibrium between forest ecological product value and farmers' livelihoods. These findings align with Reale et al., who emphasize that ecosystem-service-based sustainability requires actions that restore or maintain the ecological functions on which economic activities depend. Our results extend this argument by showing that ecological functions alone are insufficient; rather, the conversion of ecological functions into livelihood benefits depends on a compound mechanism involving finance, technology, and market access. Ecological resource endowment (X_1), while necessary, is not the dominant driver of symbiotic equilibrium—especially in the eastern region, where the interaction between resource endowment and financial development or digitalization level is more predictive than resource endowment alone.

Regional heterogeneity in these drivers is pronounced. In the eastern region, symbiotic equilibrium relies on the synergistic effects of ecological resource endowment combined with financial development, digitalization, transportation, and labor foundations. This reflects a relatively mature market environment in which ecological product value realization depends on finance-market linkages and farmers' capacity to participate in value chains—a finding consistent with Gong et al., who note that ecosystem services play differentiated roles in shaping rural livelihood resilience across ecological and non-ecological functional zones. In the central region, the interaction between ecological resource endowment and transportation conditions is the most prominent, indicating that

the key to transforming forest ecological products into livelihood benefits lies in market connectivity through logistics networks. The western region shows the strongest interaction between ecological resource endowment and labor foundation, suggesting that even abundant ecological resources require farmer participation capacity to generate stable income. This pattern echoes Angelsen et al. (2014), who find that environmental income constitutes a larger share of total livelihoods in less-developed regions, yet its absolute contribution remains constrained by limited market access and human capital. The northeastern region, by contrast, does not exhibit a clearly dominant bivariate interaction, implying that its symbiotic mechanism may still rely on separate, additive support from basic conditions rather than on a mature multivariable synergistic structure.

Taken together, these results suggest that ecological-livelihood synergy is produced by compound mechanisms rather than by a single variable. Policies that improve only ecological resources or only financial supply may have limited effects unless they are linked with technology, market access, and farmers' participation. This compound-mechanism insight carries direct policy implications for regionally differentiated interventions: eastern provinces should strengthen financial and digital transformation pathways; central provinces should improve the integration of resources, technology, and market access; western provinces should enhance farmer participation and public support; and northeastern provinces should promote industrial transformation based on existing ecological and infrastructural conditions.

3.7.5. Limitations and Future Research

Several limitations of this study should be acknowledged. First, the empirical analysis relies on provincial panel data, which are well-suited for identifying macro-level spatial patterns and policy effects but cannot fully reveal household-level mechanisms. County- or village-level data, combined with household surveys, would be necessary to examine how farmers participate in forest ecological product markets, how benefits are distributed along value chains, and whether green finance affects different farmer groups—such as smallholders versus cooperative members—unevenly. Second, the forest ecological product value index is constructed from five secondary indicators using the entropy method. While this approach reduces subjective weighting bias, alternative weighting schemes (e.g., equal weighting, principal component analysis, or expert scoring) or the inclusion of additional ecosystem-service indicators (e.g., carbon sequestration volume, biodiversity indices) might alter the index values and, consequently, the estimated symbiotic coefficients. Future research should verify the robustness of the index construction.

Third, the DID design assumes that the selection of pilot provinces is exogenous to the forest–farmer symbiotic relationship, conditional on province and year fixed effects. Although the parallel-trend test and placebo test support the credibility of this identification strategy, the establishment of green finance pilot zones may have been influenced by unobserved provincial characteristics such as pre-existing financial development or environmental quality. Future research could employ synthetic control methods or instrumental-variable approaches to further strengthen causal inference. Fourth, the LightGBM-SHAP analysis identifies associations rather than causal effects. While SHAP values reveal which symbiotic-environment variables are most strongly associated with equilibrium, they do not establish the direction of causality or rule out omitted-variable bias. Follow-up studies could use panel structural equation models or mediation analysis to test specific causal pathways from environmental drivers to symbiotic outcomes.

Finally, the study period ends in 2022, and the green finance pilot policy was still in its early implementation phase. As the policy matures and additional pilot zones are es-

tablished, longer-term evaluations may reveal whether the initial negative effect on the symbiotic relationship persists or reverses as benefit-sharing mechanisms and farmer-oriented financial products are gradually introduced. Such longitudinal assessments will be essential for determining whether green finance can ultimately serve as an inclusive pathway toward forest-based ecological prosperity.

4. Conclusions

4.1. Main Conclusions

This study examines whether forest ecological product value and farmers' livelihoods have developed symbiotically in China. By integrating allometric growth analysis, Bayesian symbiotic coefficient estimation, Lotka–Volterra interaction modeling, multi-period DID and LightGBM-SHAP interpretation, the study provides a multidimensional assessment of ecological-livelihood coordination. The results show that most provinces experienced negative allometric growth, indicating that forest ecological product value generally increased faster than farmers' income. The symbiotic coefficient rose before 2019 but declined thereafter, suggesting that the ecological-livelihood linkage weakened in the later period. The green finance pilot policy had a significant negative effect on forest–farmer symbiosis, implying that financial policy support did not automatically translate into livelihood benefits for farmers. The machine-learning results further suggest that financial development, technological progress and transportation infrastructure are important conditions associated with symbiotic equilibrium, but their effects vary across regions.

These findings have important policy implications. Forest ecological product value realization should not be evaluated only by ecological asset expansion or market transaction value. More attention should be paid to whether local farmers can participate in and benefit from ecological value chains. Green finance should be better connected with smallholders, cooperatives, forest-based industries and rural employment opportunities. Regionally differentiated policies are also needed: eastern provinces should strengthen financial and digital transformation pathways; central provinces should improve the integration of resources, technology and market access; western provinces should enhance farmer participation and public support; and northeastern provinces should promote industrial transformation based on existing ecological and infrastructural conditions. Future research could further use household-level data to examine the micro-level channels through which farmers' livelihood strategies and welfare outcomes are affected.

4.2. Policy Implications

Policy should build an integrated forest ecological product value-realization chain that connects resource-value accounting, ecological compensation, green finance, technology services, market channels, and farmers' participation. The key is to ensure that ecological value is converted into income channels that farmers can access, including employment income, operating income, cooperative dividends, and asset income. To address the transmission failures identified in the DID analysis, the following specific instruments are recommended:

Farmer-oriented green financial instruments. Rather than relying solely on conventional green credit directed at large enterprises, pilot zones should develop smallholder-accessible micro-green-loan products with reduced collateral requirements, such as forest-rights certificates, expected eco-product revenue streams, or collective guarantee schemes. Ecological product revenue-right pledge financing should be expanded, allowing farmers and cooperatives to borrow against future income from carbon sinks, under-story crops, or eco-tourism concessions. Additionally, green inclusive finance funds

should be established within pilot zones, earmarking a minimum share of green credit for rural households, village collectives, and farmer cooperatives.

Mandatory benefit-sharing and participatory governance. To prevent elite capture by platform operators and large forest farms, policy should mandate community benefit-sharing agreements in all publicly supported green finance projects that involve collective forest resources. These agreements should specify minimum income shares or employment quotas for local farmers and be monitored through third-party audits. Participatory budgeting mechanisms should also be introduced, enabling village committees to co-design ecological investment plans and ensuring that green finance projects align with local livelihood strategies rather than external corporate interests.

Digital platforms to reduce transaction costs. The SHAP analysis results suggest that digitalization and financial development are strongly predictively associated with symbiotic equilibrium; in other words, these variables carry higher predictive contributions to the equilibrium level in the model. Policy should leverage digital inclusive finance platforms to connect smallholders directly with green credit providers, eco-product buyers, and carbon-market intermediaries, thereby reducing information asymmetry and transaction costs. Blockchain-based traceability systems can further enhance the market value of farmer-produced ecological products, allowing households to capture premium prices that are otherwise absorbed by intermediaries.

Regionally differentiated intervention bundles. Given the pronounced regional heterogeneity identified in the L-V and SHAP analyses, a uniform national policy is insufficient.

In eastern China, policy should prevent ecological-product value from being captured mainly by capital or platforms. Green finance, forest carbon-sink finance, ecological product trading platforms, and digital marketing should be linked with contract farming, profit-sharing, employment absorption, and collective-economy dividends. Special attention should be paid to ensuring that digital finance and platform economies include smallholders rather than displacing them.

In central China, policy should strengthen logistics, cold-chain systems, regional brands, and technical services for the understory economy, forest products processing, forest-based health and wellness, and rural ecological tourism. Transportation–technology–resource integration is the critical compound mechanism; green finance should be directed toward infrastructure and processing capacity that connect farmer-produced ecological goods with external markets.

In western China, ecological compensation, public-benefit forest management, follow-up support for returning farmland to forest, and ecological-industry subsidies should be combined with mechanisms that expand farmers' participation in management, understory production, forest tourism, and specialty forest-product processing. Labor–resource co-development programs should be financed, combining green credit with technical training to ensure that ecological resource advantages translate into household capabilities and income.

In northeastern China, policy should focus on industrial transformation, forest resource utilization, infrastructure improvement, and market-oriented ecological consumption. Given the absence of a dominant multivariable synergistic structure in this region, sequenced, additive support is needed: first improving transportation and financial access, then linking these foundational conditions with ecological product processing and rural enterprise development.

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X.H. and D.C.; writing—review and editing, Y.H., X.H. and D.C.; visualization, Y.H. and X.H.; supervision, L.X.; project administration, L.X.; funding acquisition, L.X. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

DID	Difference-in-Differences
GEP	Gross Ecosystem Product
GDP	Gross Domestic Product

Appendix A

Table A1. Conceptual Definitions of Symbiosis-Related Ecological-Economic Terms.

Term	Biological Origin	Operational Definition in This Study	Socio-Forestry/Policy Interpretation
Symbiosis	Close, long-term interaction between different species	The co-evolutionary and bidirectional interaction between the forest ecological product value system and the farmers’ livelihood system	Whether forest ecological value growth and rural income improvement move in tandem, diverge, or conflict over time and space
Mutualism	Both species benefit	Both systems positively reinforce each other: forest ecological product value growth enhances farmers’ income, and livelihood improvement in turn	A “win-win” policy outcome where ecological conservation and rural prosperity are mutually reinforcing

Term	Biological Origin	Operational Definition in This Study	Socio-Forestry/Policy Interpretation
		supports sustainable forest value realization	
Commensalism	One benefits, the other is unaffected	An asymmetric relationship where one system gains while the other is neither helped nor harmed	Forest value grows without translating into farmers' income gains, or income rises without contributing to forest value (e.g., off-farm employment)
Parasitism	One benefits at the expense of the other	Unidirectional extraction where one system thrives while the other is depleted	Either short-term income gains rely on ecological overuse, or ecological accumulation occurs without livelihood returns.
Symbiotic environment	External biotic and abiotic conditions affecting species interactions	The institutional, market, technological, infrastructural, and policy conditions that enable or constrain the forest–farmer relationship	External drivers—such as green finance, transportation networks, digital platforms, government support, and labor capacity—that determine whether ecological value is converted into inclusive livelihood benefits

Table A2. Posterior Diagnostic Statistics of Bayesian Hierarchical Model Parameters.

	Mean	Sd	Hdi_3%	Hdi_97%	Mcse_mean	Mcse_sd	Ess_bulk	Ess_tail	R_hat
mu_F	0.02	0.005	0.01	0.029	0	0	637	1292	1.01
mu_L	0.033	0.004	0.025	0.04	0	0	901	1407	1
sigma_F	0.024	0.001	0.022	0.026	0	0	4192	3104	1
sigma_L	0.024	0.001	0.022	0.026	0	0	3423	2499	1
tau_province_F	0.021	0.003	0.016	0.027	0	0	860	1662	1.01
tau_province_L	0.009	0.002	0.005	0.013	0	0	1473	1964	1
tau_year_F	0.009	0.003	0.003	0.014	0	0	1324	1816	1
tau_year_L	0.011	0.004	0.006	0.017	0	0	974	1712	1.01

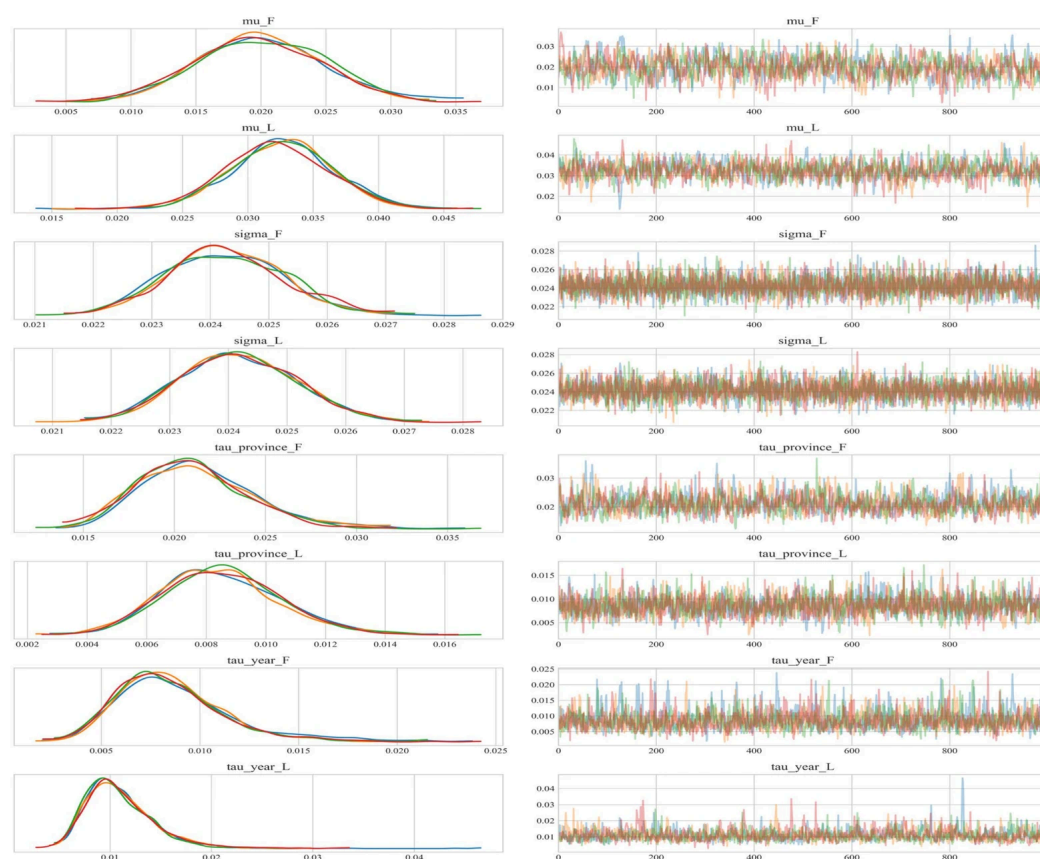


Figure A1. Bayesian trace plots.

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