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REVIEW ARTICLE

Analysis of the synergistic mechanism of forest eco-economic system

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ABSTRACT

Based on the collective forest with common use rights, the social-ecological system analysis framework and autonomous governance theory proposed by Elinor Ostrom are introduced in the forest eco-economic system to analyze the interaction logic among the first-level subsystems and the secondary variables of the forest eco-economic system and the variables related to the autonomous governance of the system to explore the synergistic mechanisms affecting the forest eco-economic system. The results show that: in the case of information asymmetry, collective actions of governmental and non-governmental organizations will aggravate the dilemma of forest eco-economic synergistic development; actors extract forest resource units from the forest resource system to achieve economic benefits; and renewable resources of forest ecosystems can be sustained in the long term when the average extraction rate of humans from forest ecosystems does not exceed the average replenishment rate.

Keywords: Forest Eco-economic System; Sustainability; Autonomous Governance; Interaction Analysis

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1. Introduction

Forests are both an important ecological barrier and an important industrial base for the national economy[1]. From traditional forestry, which pursues economic goals, to modern forestry, which protects the environment and balances economic development, the essence of forestry development is to continuously solve the problem of forest resource management, which is inseparable from the interaction between human and ecology, which also involves the analysis of the interaction and synergy mechanism between forest ecology and forestry economy. Therefore, how to correctly grasp the multifaceted interaction between forest ecology and forestry economy is the key to the development of forestry and forest management; how to identify the key variables and formation mechanism of the coupled forest ecology-economy system, and how to put forward targeted policy recommendations for synergistic development is a hot issue in forestry sustainable development research. In terms of research content, scholars have mainly studied forest ecology-economy synergy in terms of ecological-economic coordination theory[2], ecological service function value[3,4], social-ecological system[5,6] and forest resource governance[7,8], and concluded that forests have complex ecological benefits, economic benefits and social benefits. In terms of research methods, scholars mainly apply the principles of system theory[9-11] and related mathematical methods[12-15] to analyze and describe the coupled synergistic relationship between ecology and economy, and find that forest ecology-economy system has various coupling states in different regions and different stages. From a cross-disciplinary perspective, domestic scholars have applied the

Social-Ecological Systems (SES) analytical framework proposed by American scholar Elinor Ostrom to study the forest resource governance[7,8], irrigation governance[16], and collective forest rights system reform[17,18] in China. The SES analytical framework can provide ideas for forest resource management and rural irrigation management in China. First, based on the idea of system coupling proposed by Ren[11], many scholars use coupling coordination function and secondary data to analyze the coupling status of environmental and economic subsystems. Second, most of the existing studies have taken forest management models, forestry cooperatives and other specific subjects as the objects of investigation, while there are fewer results of in-depth studies on the interaction between multiple subjects and macro forest ecology and forestry economy; third, the SES analysis framework is mostly applied to macro-level Third, the SES analysis framework is mostly applied to the macro-level analysis of forest resource governance in China[7,8], while few research results have used the SES analysis framework to study the mechanistic analysis of forest ecology and forestry economy and to investigate and explore the secondary variables under the subsystem and the core variables affecting autonomous governance[18]. The synergy of forest ecology-economy system refers to the maximization of the output of economic and ecological products of the forest ecology-economy complex system while maintaining its health and stability, and if organizational and human factors are taken into account, it still belongs to the socio-ecological system category. Changes in forest resource development (or growth) can be quantified to reflect the process and results of governance. Therefore, the SES analysis framework and autonomous governance theory are introduced to analyze the interaction logic among the subsystems at the lower level of the forest eco-economic system, and to explore the secondary variables of the forest eco-economic system and the related variables that affect the autonomous governance of the system, taking the collective forest with common use rights as the research object and the development of Chinese forestry. The results of the study can provide explanations for the intrinsic synergistic mechanisms affecting the forest eco-economic system.

2. Overview of the social-ecological systems analysis framework

2.1 Theoretical lineage of the social-ecological systems analysis framework

In 1960, the American scholar Harding's paper "The Tragedy of the Commons"[19] and Olson's paper "The Logic of Collective Action"[20] raised the same issue: public pond resources are overexploited and consumed due to free access and unlimited demand, which leads to "tragedy of the commons". For this reason, scholars have proposed the solution of complete privatization of public resources or forced government intervention. In order to dig deeper into the essence of the tragedy of the commons, the research team of Elinor Ostrom started to establish monitoring stations of forestry research organizations in 15 countries in 1992, and conducted field surveys for more than 20 years to monitor the autonomous governance of forest resources in more than 10 villages of these countries. We propose a theory of autonomous governance and a framework for institutional analysis of social-ecological system sustainability that includes public pond resources such as forests, pastures, water resources, fisheries, and climate.

2.2 The operating mechanism of the social-ecological system level subsystem

The coupled social-ecological system means that human actions and ecological structures are closely linked and interdependent, forming a social-ecological system with mutual coupling and multidimensional interaction. In 2009, Eleanor Ostrom proposed a multi-level nested SES analytical framework[5]; in 2014, McGinnis and Eleanor Ostrom developed a multi-level nested SES analytical framework[6]. In 2014, McGinnis and Elinor Ostrom revised the SES analysis framework to form a logical relationship between subsystems at the social-ecological system level (**Figure 1**)[6]. The revised social-ecological system framework generally describes the interactions among four first-level subsystems, namely resource systems, resource

units, governance systems, and actors, in social, political, and economic contexts and externally linked ecosystems, interacting in specific action contexts to achieve the social, ecological, and economic benefits of the ecosystem. At the same time, the results of the interactions are reflected in the 4 subsystems, thus forming a circular structure of interactions. In political and cultural contexts, resource users, as efficient actors in managing and using the resource system, take resource units from the resource system and then ensure its continuous and efficient operation through rules and procedures efficiently governed by the governance system[21]. Resource systems are characterized by properties such as complexity and irrecoverability, and the operation of social systems affects them; therefore, it is particularly important to examine and analyze the internal mechanisms between social-ecological systems and their constituent elements.

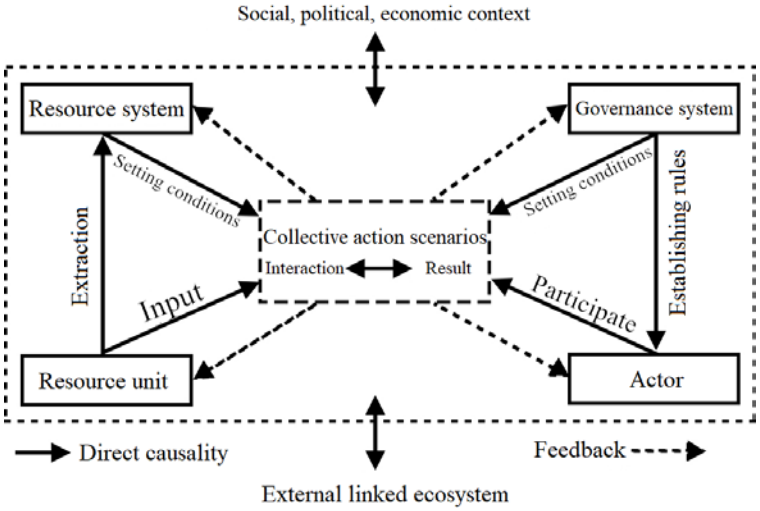

Figure 1. Revised SES framework with multiple first-tier components.

3. Analysis of the synergistic mechanism of forest eco-economic system

3.1 Interaction of forest ecosystem-economic system subsystems

Forest eco-economic system is a natural resource ecosystem based on natural forces and subject to human intervention[23], which consists of three first-level subsystems: forest ecosystem, forestry economic system and social system, each of which interacts with each other independently. The synergistic development of forest ecology-economy system refers to the scientific and efficient use of multiple functions of forests within the carrying capacity of forest ecosystems, so that forest resources can provide products and services for people's production and living needs, maximize the economic value of forest resources, and maintain the economic form of coordinated development of forest ecology and forestry economy[11]. As a special composite system, the forest ecology-economy system harbors a complex variety of inter- and intra-system circulation modes and pathways[10], and its dynamic coupling process is governed by both natural and economic and social laws. The forest ecology and forestry economy balance is based on ecological balance, thus, the concept of forest management changes from the traditional "timber utilization" to "ecological utilization"[1], i.e., from timber production to the governance problem of balancing ecological, economic and social objectives of all parties Transformation.

3.2 Explaining the synergistic mechanism of forest eco-economic systems using the SES analytical framework

Introducing the SES analytical framework to forest eco-economic systems[5], the interaction between forest ecosystems and forestry economic systems in social, political and economic contexts is essentially an interaction between four first-level subsystems: forest resource systems, forest resource units, governance systems and actors to achieve

ecological, social, economic and governance benefits of forest ecosystems in specific action contexts of forest management and conservation (**Figure 2**). The ecological, social, economic and governance benefits of forest ecosystems are realized in specific action situations of forest management and conservation (**Figure 2**). At the same time, the ecological, social, economic, and governance benefits of the forest eco-economic system interact positively or negatively with these four first-level subsystems, thus forming a circular structure of interaction.

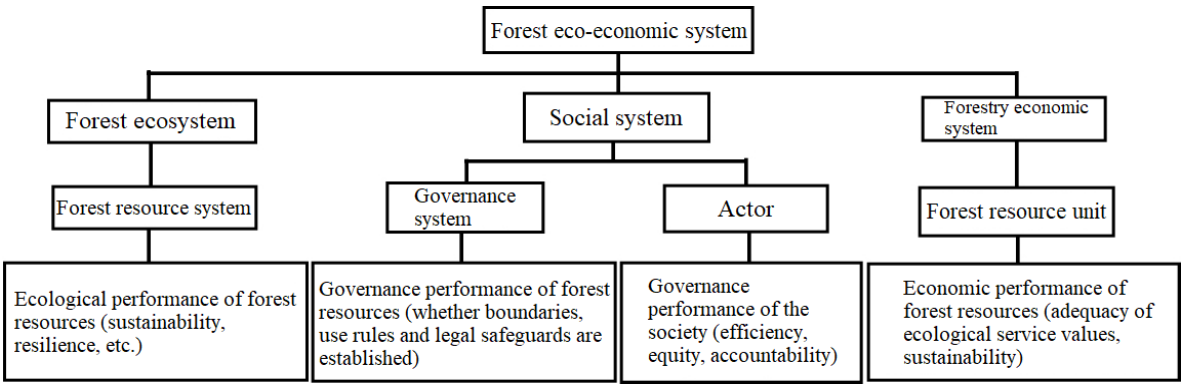

Figure 2. Composition diagrams of forest eco-economic system.

In a forest eco-economic system, the forest resource system is a forest ecosystem storage variable; forest resource units are the amount that actors take up or participate from the forest resource system; actors are those who have specific legal rights to extract forest resources and are also participants who extract forest resource units from the forest resource system; the governance system is the governmental or nongovernmental organizations that make forest resource. The governance system refers to governmental or non-governmental organizations that set rules related to the management and administration of forest resources. Actors can not only use or consume the forest resource units they extract, but also use them for productive inputs and thus gain economic benefits. It is possible to determine the rate of forest resource replenishment based on reasonable conditions that maximize the flow without damaging the storage or the forest resource system itself, the forest resource system as a stock, and the harvest of forest resource units as a flow, as actors occupy and use the forest resource system. The average rate of human extraction from the forest ecosystem does not exceed the average rate of replenishment for the renewable resources of the forest ecosystem to be sustainable in the long term. Actors take forest resource units from the forest resource system for economic benefits but also for the risk of damaging the forest resource system, and the governance system addresses the supply, commitment, and monitoring of the system through users, governmental organizations, and non-governmental organizations, among others.

3.3 Analysis of secondary variables in forest eco-economic systems

The central challenge in diagnosing the sustainability or collapse of forest eco-economic systems is to identify the key variables of complex systems. An important contribution of the SES analytical framework is to uncover the important factors affecting the sustainability of social-ecological systems through years of field research[24]. Therefore, based on the secondary variables of the core subsystem listed by Elinor Ostrom, the secondary variables under the primary core system of the forest eco-economic system framework are proposed in the context of the characteristics of collective forest areas in China (**Table 1**).

Resource types (RS1) include natural forests and planted forests, among which natural forests are mainly protected. Active protection of natural forests cannot be separated from forest management, which meets the demand with greater functionality by improving the quality of forest stands. Planted forests, on the other hand, are fully marketed and the actors are responsible for their own profits and losses, but most of them are roughly managed and

Table 1. Analysis framework of a forest Eco-economic system

First-level subsystem	Symbols	Secondary variables	Symbols
Social, economic and political context	*S*	Degree of economic development	S_1
		Demographic trends	S_2
		Degree of political stability	S_3
		Government resource policies	S_4
		Market incentives	S_5
		Media organization	S_6
Forest resource system	*RS*	Resource type (e.g., natural forest, plantation forest)	RS_1
		Clear system boundaries (definition of forest land boundaries)	RS_2
		Scale of forest resource system (forest area, etc.)	RS_3
		Infrastructure (access to water, electricity, roads and housing)	RS_4
		Forest production system (natural productivity of forests, economic productivity of forestry)	RS_5
		Ability to maintain self-balance	RS_6
		Predictability of system dynamics	RS_7
		Resource storage characteristics	RS_8
		Location distribution	RS_9
Forest resource units	*RU*	Mobility of resource units	RU_1
		Growth and renewal rate (scientific harvesting and renewal methods, reasonable tree species and age structure)	RU_2
		Interaction of resource units	RU_3
		Economic value (forest resource value)	RU_4
		Number of resource units	RU_5
		Clear markers	RU_6
		Spatial and temporal distribution (temporal and spatial distribution of forest resources)	RU_7
Governance System	*GS*	Governmental organization (management)	GS_1
		Non-governmental organizations (forest management and forest protection organizations)	GS_2
		Network structure (vertical governance structure)	GS_3
		Property rights system (collective ownership, individual ownership)	GS_4
		Operational rules (behavior of forest resource actors)	GS_5
		Collective choice rules (active inspection and monitoring of forest resource status and	GS_6
		Legal rules (degree of sanction depends on content and severity of violation)	GS_7
		Conflict resolution mechanisms (weighing costs and benefits of conflict resolution)	GS_8
Actors	*A*	Number of users of forest management or conservation	A_1
		Socio-economic attributes of actors	A_2
		History of resource use	A_3
		Geographical relationship between actors and resources	A_4
		Leadership/entrepreneurship	A_5
		Social norms/social capital	A_6
		Awareness/thinking about forest eco-economic systems	A_7
		Degree of dependence of actors on forest resources (high, medium, low)	A_8
		Technologies used for forest management (genetic breeding, cultivation, etc.	A_9
Interaction	*I*	Level of resource harvesting	I_1
		Information sharing	I_2
		Consultation processes	I_3
		Conflict situations (forest rights, system boundaries, and timber disputes)	I_4
		Investment activities (forestry investments are at low levels)	I_5
		Lobbying activities	I_6
		Self-organization activities	I_7
		Network structure activities	I_8

Table 1. (Continued)

First-level subsystem	Symbols	Secondary variables	Symbols
Outcomes	*O*	Social performance assessment (e.g., efficiency, equity, accountability, sustainability, etc.)	O_1
		Ecological performance assessment (excessive deforestation, recoverability, biodiversity)	O_2
		Economic performance assessment (economic income from forestry, sustainability)	O_3
		Governance performance assessment (presence of conflict)	O_4
Externally linked ecosystems	*ECO*	Climate conditions	EO_1
		Pollution	EO_2
		Energy and information flows in social-ecological systems	EO_3

the operators need policy support and technical guidance (A9). Since the implementation of a new round of collective forest rights system reform in 2003, some forest land property rights boundaries are still unclear (RS2) and there is no corresponding conflict resolution mechanism (GS8), which leads to forest rights disputes (I4) and affects forest management actors' difficulty in responding rationally to changes in market demand. Under the reform of collective forest rights system and supporting policies, the management rights of collective forests with common property rights have been activated, and some new forestry management organizations (GS2) have emerged, but due to their short operating history (A3), the operating rules (GS5), collective choice rules (GS6), legal rules (GS7) and supervision mechanisms (GS8) are not perfect; governmental organizations (GS1) and non-governmental organizations (GS2) under the information asymmetry are not sufficiently well established. The collective action of governmental organizations (GS1) and non-governmental organizations (GS2) under information asymmetry has exacerbated the dilemma of forest eco-economic development.

Table 2. Related variables influencing self- governance of SES

First-level subsystem	Symbols	Secondary variables	Symbols
Resource system	*RS*	Forest resource size	RS_3
		Forest production system	RS_5
		Predictability of changes in system dynamics	RS_7
Resource unit	*RU*	Resource unit movability	RU_3
Actor	*A*	Number of users of forest management or conservation	A_1
		Leadership/entrepreneurship	A_5
		Social norms/social capital	A_6
		Perceptions/ways of thinking about forest eco-economic systems	A_7
		Actor's dependence on forest resources	A_8
Governance system	*GS*	Collective choice rules	GS_6

3.4 Analysis of relevant variables affecting the autonomous governance of forest eco-economic systems

Ten variables related to autonomous social-ecological system governance[5] were applied (**Table 2**) to examine and explain the secondary core sub-variables related to autonomous governance, which are also key variables for sustainable development or system collapse of forest eco-economic systems.

3.4.1 Scale of the forest resource system

Defining boundaries requires high costs and is not suitable for autonomous management when the area of forest management areas is too wide[5]. After the comprehensive implementation of the collective forest rights system reform, most of the forest land is contracted to households, which makes it difficult to form large-scale management, resulting in the reduction of marginal rewards and motivation of forest farmers to invest in forest land. In order to improve this pattern, there is an urgent need to expand the scale of production and implement autonomous governance through self-organization such as association and cooperation, thus improving

the forest management efficiency of foresters. From the perspective of forest resources, factors such as the high cost of defining forest land scale boundaries and the difficulty of obtaining information on forest resources also indirectly affect whether different forest scales implement autonomous governance. Based on the development of China's forestry industry, on the one hand, the reform of China's collective forest rights system has basically solved the problem of different property rights belonging to the Elinor Ostrom resource system and resource units; on the other hand, forestry professional cooperatives and other forest management organizations have re-integrated and scaled up the scattered property rights and finely operated forestry, effectively solving the problem of low operation of small property rights, reflecting the Cooperatives and other forestry cooperative organizations autonomous governance spirit[8]. Therefore, the scale of forest resource system is an important variable for the implementation of autonomous governance by actors.

3.4.2 Forest production system

Forest ecosystems include natural productivity of forests and forest eco-economic productivity, and the productivity of forest resource systems has a curvilinear effect on the autonomous governance of forest resources[5]. Forest eco-economic productivity refers to the ability of human to develop, use and protect the forest eco-economic system to obtain forest products and ecological services, and to improve forest quality, maintain and improve the reproduction of forest resources[1]. In order to improve forest productivity, we need to consider its input factors[1]: (1) labor factor, giving full play to the subjective initiative of forest resource actors; (2) labor object and labor material factor, the labor object is the forest ecological-economic system, and labor material is a complex material system, including the material and equipment conditions necessary in the forestry management process, such as fertilizers, pesticides and other economic factors, but also including water resources and other natural environment; (3) science and technology. Science and technology play an important role in forest management, such as the use of aircraft seeding, seed selection and breeding; (4) information element. It is the transmission element of the system, including market information, biological information and forest resource information. Based on the fact that China's forestry economic growth model mainly relies on the capital factor drive, while the labor factor, labor objects, labor materials, science and technology factors and policy and system factors have unreasonable inputs[24], only by realizing self-organized forest management can each production factor be reasonably allocated, so as to improve forestry production efficiency and establish an intensive forest management model.

3.4.3 Predictability of system dynamic changes

Forest resource systems tend to be more predictable than aquatic ecosystems, and some fishery systems approach mathematical chaos, and actors develop harvesting rules based on the predictability characteristics of forest resource systems[5]. Unpredictability at small scales may lead actors in forest systems to organize their operations at larger scales to improve overall predictability and also enhance overall operational capacity and risk resilience.

3.4.4 Resource unit mobility

Managing and operating resource units that are mobile requires high costs. In forest resources, wildlife is mobile compared to fixed units such as trees and plants. Therefore, it is less likely that autonomous management of wildlife will be implemented.

3.4.5 Number of actors

Forest management is characterized by long growth cycles, slow results, and low benefits, so the group size can reduce the transaction costs of self-organization and autonomous governance[5]. In the case of community forests, which are very costly to operate, then larger groups are able to mobilize more of the necessary labor and other resources. Thus, group size is always associated with the implementation of autonomous governance of forest resources, but its effect on self-organization depends on other variables of the forest eco-economic system and the type of management tasks involved.

3.4.6 Leadership/entrepreneurship

Leadership refers to the ability to run and manage a forestry enterprise and the ability to innovate. In foreign countries, forestry business subjects have the necessary skills and practical experience as leaders and entrepreneurs, and at the same time are respected as local leaders and are more likely to achieve autonomous governance[5]. Under the rural revitalization strategy, leaders such as science and technology specialists, village cadres, hometown-loving sages and heads of forestry cooperative organizations are more likely to promote autonomous governance of forest resources.

3.4.7 Social norms/social capital

Transaction cost theory clarifies that rule making reduces transaction costs[24]. The central government is the developer, promoter and innovator of the collective choice principle, while local governments are the implementers of the operational principle. Chinese forestry policy implementation and enforcement relies on a top-down management model. If local governments adopt selective implementation in policy implementation, or even seek private interests in the process of policy implementation, while the limited rational higher authorities consider that supervision will cost high supervision costs and choose sub-optimal principles, thus failing to achieve effective supervision. Therefore, it is necessary to speed up the transformation of the functions of grassroots forestry authorities, strengthen the sense of public service, and establish a more efficient management system. In forest management, transaction and monitoring costs can be reduced if business actors keep their promises, reciprocity and ethical standards.

3.4.8 Cognitive/thinking approaches to forest eco-economic systems

Collective forestry development is the operation process of a composite system coupled by forestry economic subsystem and forest ecological subsystem, and forestry industry needs to be developed under the premise of considering the carrying capacity of the ecosystem. If actors such as forestry cooperatives, family forestry farms and forestry enterprises have knowledge of forest eco-economic systems, awareness of environmental protection, forest management skills and systemic thinking, they can reduce the cost of autonomous governance.

3.4.9 Actors' dependence on forest resources

In the case of Elinor Ostrom's successful autonomous organization, actors either rely primarily on the forest resource system for their livelihoods or place a high value on the sustainability of the forest resources[5]; otherwise, organizing and maintaining an autonomous governance system is not worth the investment cost. Actors pursue short-term economic benefits and disregard environmental conditions to plant large areas of fast-growing and productive forests, etc., with the risk of damaging the ecological environment; actors pursue long-term economic benefits such as the stand structure and quality of forest resources to promote the coordinated development of forest ecology and forestry economy.

2.4.10 Collective choice rule

At the level of collective choice rules, actors have a great deal of autonomy to participate in the formulation and implementation of rules, and to adjust them as they evolve over time and are optimized over generations of experience. For this reason, these rules are highly operational and applicable, while promoting mutual monitoring of compliance among actors, thus reducing monitoring costs and social costs.

3.5 Using autonomous governance theory to explain the synergistic mechanism of forest eco-economic systems

The essence of public pond resource governance theory is to seek autonomous organization and autonomous governance of social-ecological systems beyond the limitations of the market and the government[8], and to this end, based on the realities of forest management in China, and in accordance with the reform requirements of "decentralization", we aim to enhance community governance capacity under the legal framework of the state to make forest management In this regard, based on the real situation of forest management in China, we aim to enhance the community governance capacity under the national legal framework in accordance with the reform requirements of "decentralization and man-

agement", so that the forest management owners have more autonomy. The central government formulates collective forestry development policies, local governments implement collective forestry development policies, and cooperation between governments and forest management entities at all levels is an effective guarantee of autonomous governance. Elinor Ostrom's research strategy analyzes the process of autonomous organization and autonomous governance in small-scale forest resource systems, and the central question is how a group of interdependent agents (actors) can organize and govern themselves and obtain sustainable co-benefits while resisting the temptation of free-riding, responsibility avoidance, or other opportunistic behaviors. Issues to be considered in the implementation of autonomous organization and governance of forest resources[25]: (1) how to increase the initial possibilities of autonomous organization; (2) how to enhance people's ability to address institutional provisioning, commitment, and monitoring through continuous self-organization; and (3) how to enhance the ability to address autonomous governance of forest resources through autonomous organization when there is no external assistance of some kind. The four internal variables that influence the choice of rational individual strategies of forest resource actors: expected benefits, expected costs, intrinsic norms, and discount rate. Nine environmental variables are involved in the problem of institutional provision of forest resources in collective forest areas with common property rights: number of forest resource actors, size of forest resources, spatial and temporal conflict of forest resource units, existing conditions of forest resources, market conditions of forest resource units, number and type of conflicts, availability of information on these variables, existing rules used and proposed rules.

4. Conclusion

Collective action of governmental and non-governmental organizations under information asymmetry exacerbates the dilemma of synergistic development of forest ecological economy. The macro-ordered structure of the forest eco-economic system depends on the correlation and functional synergy among the system components, i.e., attention should be paid not only to the role of each single factor, but also to the linkages among the secondary variables within the system and between the system and the external social and economic-political context and ecological environment. As forest management is a basic industry and a public welfare undertaking, the key to the synergistic development of forest ecology and forestry economy lies in enhancing the capacity of autonomous community governance within the legal framework of the state, and how the actors of autonomous forest management governance can supply, commit, monitor and obtain sustainable co-benefits from the system while resisting the temptation of free-riding, responsibility avoidance or other opportunistic behaviors. Improving the autonomous governance capacity of forestry cooperatives and sound management systems of forest ecosystems is to achieve sustainable management of forest resources. Based on the complexity and specialization of coupled forest ecological systems, interdisciplinary or cross-disciplinary research can study and understand complex forest ecological-economic systems from multiple perspectives. For this reason, cross-disciplinary hit-and-miss research is more conducive to comprehensive analysis and identification of mechanisms affecting the synergistic development of forest ecology and forestry economy. In addition, things and contradictions are universally related, and the synergistic development of forest ecology and forestry economy is contradictory in nature, and its synergistic nature involves many stakeholders. By strengthening the empirical study of the macro forest ecology-forestry economy interaction, the application value of the SES framework for weighing the synergistic sustainable development of forest ecology and forestry economy in China is thus highlighted.

Conflict of interest

The authors declare that they have no conflict of interest.

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