

Wang, Kun; Feng, Yu; Liu, Siyao

Article

Analyzing the innovation ecosystem of China's major science and technology projects: From the ecological and systems science perspective

Project Leadership and Society (PLAS)

Provided in Cooperation with:

International Project Management Association (IPMA), Zurich

Suggested Citation: Wang, Kun; Feng, Yu; Liu, Siyao (2024) : Analyzing the innovation ecosystem of China's major science and technology projects: From the ecological and systems science perspective, Project Leadership and Society (PLAS), ISSN 2666-7215, Elsevier, Amsterdam, Vol. 5, pp. 1-11,
<https://doi.org/10.1016/j.plas.2024.100156>

This Version is available at:

<https://hdl.handle.net/10419/339910>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

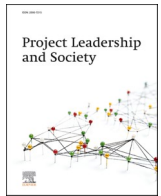
Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by/4.0/>



Empirical Research Paper

Analyzing the innovation ecosystem of China's major science and technology projects: From the ecological and systems science perspective

Kun Wang^a, Yu Feng^{b,*}, Siyao Liu^b

^a China Mobile Beijing Branch, Beijing, 100032, China

^b School of Economics and Management, Beijing University of Posts and Telecommunications, Beijing, 100876, China

ARTICLE INFO

Keywords:

National major science and technology projects
Innovation ecosystem
Innovation community
System construction
Megaprojects
High-quality development

ABSTRACT

The National Major Science and Technology Projects in China are characterized by government leadership, interdisciplinary collaboration, and international cooperation. However, challenges such as insufficient innovation capacity and inadequate commercialization of scientific achievements are becoming increasingly prominent. This paper adopts the conceptual framework of natural ecology to examine these projects. By utilizing theories and methods from ecology and systems science, we draw an analogy between the innovation ecosystem of China's national major science and technology projects and the structure of ecological systems, analyzing the interrelationships among the components of the innovation ecosystem and establishing the four-level model. The findings indicate that collaboration and policy guidance among the enterprise, research, and auxiliary innovation layers promote scientific output and innovation, while the external environmental layer provides robust support and safeguards, collectively driving the development of the innovation ecosystem. We study the operational mechanisms of the innovation ecosystem in depth, identifying mechanisms of competitive symbiosis, coordination, and sharing. These mechanisms work together throughout the project management process, offering new insights for enhancing the scientific and effective management of these projects. The national innovation ecosystem and high-quality development mutually reinforce and complement each other. As a critical pathway to high-quality development, our study provides new approaches to addressing the challenges of insufficient innovation capacity and the difficulty in translating scientific achievements into practice, contributing to the optimization of resource allocation, and the deep integration of technological innovation with economic and social development.

1. Introduction

Megaprojects are generally defined as those costing more than \$1 billion (Flyvbjerg, 2014), which have long construction durations, high complexity and significant impacts on social and economic development (Han et al., 2024). National major science and technology projects in China are strategically significant undertakings aimed at achieving national objectives through breakthroughs in core technologies and resource integration. These projects, such as the development of major new drugs and next-generation broadband wireless mobile communications, are central to China's scientific and technological advancement. Characterized by long implementation periods, extensive project scope, numerous participants, and complex interactions among knowledge resources, these projects can be viewed as complex, large-scale systems operating within dynamic environments (Adner, 2017).

The concept of high-quality development, introduced by China in 2017, builds upon the principles of sustainable development while incorporating a broader, more integrated approach. This framework emphasizes the interconnectedness of sustainable economic growth with qualitative improvements, efficiency gains, and environmental responsibility, going beyond mere quantitative expansion. Developing an innovation ecosystem specifically designed for major national projects is recognized as a key strategy and foundational support for advancing this development trajectory (Zhao, 2024). The relationship between this ecosystem and high-quality development is reciprocal, with each facilitating the other's progress. High-quality development provides a supportive environment that nurtures the innovation ecosystem, while the ecosystem, in turn, plays a crucial role in achieving the objectives of high-quality development (Guo et al., 2024). Both share aligned goals, pathways, and strategies, focusing on innovation-driven growth,

* Corresponding author.

E-mail address: fyfeng@bupt.edu.cn (Y. Feng).

<https://doi.org/10.1016/j.plas.2024.100156>

Received 15 December 2023; Received in revised form 13 September 2024; Accepted 21 September 2024

Available online 23 September 2024

2666-7215/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

environmentally sustainable development, and coordinated progress. Their coevolution creates a mutually reinforcing dynamic that amplifies their collective impact, guiding a sustainable development pathway forward (Lehtinen et al., 2019).

Reports continue of project's having 'failed', running overtime and over budget (Love et al., 2011). This suggests that, there still remain gaps in our knowledge concerning megaprojects. However, the ecosystem perspective offers a robust framework for understanding existing complex systems (Malherbe, 2022). The concept of an ecosystem, which originates from the interdependence of firms across organizations and activities (Adner, 2006), is a multifaceted construct studied from various perspectives. And ecological systems theory, which has yielded significant insights in the field of ecology (Jin et al., 2022), is increasingly integrated with modern systems science to form a comprehensive methodological discipline. This interdisciplinary approach has gradually permeated various fields (Daniel, 2019), including project management, enterprise management, and industrial development. Some scholars have explored these topics from the perspectives of commercial ecosystems (Fuller et al., 2019), entrepreneurial ecosystems (Theodoraki and Catanzaro, 2022), and technological ecosystems (Brem and Nylund, 2022), concluding that these ecosystems interact and co-evolve.

In theoretical research, scholars utilize various approaches such as game theory (cooperative game theory, competitive game theory, evolutionary game theory) and optimization theory (Yang, 2007). For example, Xu et al. (2023) employed evolutionary game theory to model an innovation ecosystem with two groups, analyzing value co-creation decision-making in digital innovation systems. Paasi (2023) explored the dynamics of innovation ecosystems using a system dynamics approach, aiming to support the creation and coordination of innovation ecosystems for enhanced success. Zeng (2022) revealed the interactive relationships within the enterprise green innovation ecosystem by developing a three-dimensional dynamic evolution model.

System science theory, which examines the nature, behavior, and interactions of complex systems, provides a valuable lens for analyzing major national projects. By integrating system science with these projects, a more systematic perspective can be achieved. The holistic approach of systems science theory helps interrelate different components to form a comprehensive ecosystem framework. Additionally, systems science theory emphasizes complexity, enabling a deeper understanding of interactions and relationships within the system (Davies et al., 1988). This approach allows for a better analysis of dynamic processes and evolutionary patterns in the innovation ecosystem. Given the complexity of national major science and technology projects, this paper links the concept of ecosystems with ecological and systems science theories to analyze the innovation ecosystem's structure. The goal is to explore effective ways to enhance national scientific innovation capabilities.

Current literature predominantly focuses on the relationships between specific components, such as the collaboration between state-owned enterprises and research institutions (Dai et al., 2024), university-industry partnerships as a key pathway for industry-academia cooperation (Jin et al., 2023), the dynamics between governments and enterprises during crises (Feng and Zhu, 2024), and the relationship between government funding structures and universities (Wang et al., 2023). On the other hand, some scholars have constructed system frameworks for national major projects from various perspectives. For instance, Peng (2023) constructed an enterprise business management system based on intelligent data technology and a big data analysis framework. Gilbert Silvius (2022) examined the integration of sustainability into organizational strategy, portfolio management, and project management, establishing a conceptual framework. However, a comprehensive framework for the national innovation ecosystem of major science and technology projects has not yet been thoroughly examined.

Recent literature suggests that contemporary innovation processes

must extend beyond isolated innovations and individual organizations (Kapsali, 2011), a more systematic perspective is required to examine the innovation ecosystem frameworks of major projects. Consequently, by utilizing ecological terminology, this paper compares and elucidates the principles of national major science and technology innovation activities, ultimately discussing the construction of a national major science and technology innovation ecosystem. In contrast to other frameworks, the framework proposed in this paper considers the relationships among various components—enterprises, governments, and other stakeholders—from an ecosystem perspective, enabling a more comprehensive understanding of the structural framework of the innovation ecosystem.

2. Connotation of innovation ecosystem of national major science and technology projects

2.1. Definition of innovation ecosystem of national major science and technology projects

Based on the characteristics of national major science and technology projects, this paper explores the innovation ecosystem of these projects by utilizing ecological theories and methods. It explains the relationships among various stakeholders involved in the implementation of major science and technology projects and their interactions with the environment. This approach reflects the coupling between the national major science and technology innovation system and the broader ecosystem. A megaproject innovation ecosystem is defined as a balancing structure comprising multilateral sets of actors organized around a central megaproject, embedded within favorable environmental conditions to create and appropriate value through innovation.

In this study, we adopt the concept of the innovation ecosystem for China's national major science and technology projects. It aims, on one hand, to address the innovation ecosystem issues of these projects by referencing ecological theories and methods. On the other hand, it seeks to correct the historical oversight of environmental factors in the technological innovation activities of engineering projects. It is important to clarify that this paper does not equate the innovation environment strictly with the ecological environment but borrows terminology from ecology to more effectively compare and explain the underlying causes of innovation and technological activities in major national science and technology projects.

Considering the ecological characteristics of major national science and technology projects in terms of their constituent elements and operational processes, and based on previous research (Huang, 2007; Li, 2008), a preliminary comparison table has been constructed. This table aligns the innovation system elements of major national science and technology projects with those of natural ecosystems, as shown in Table 1.

2.2. Characteristics of the innovation ecosystem of national major science and technology projects

Scientific and technological innovation is an essential requirement for countries to enhance their competitive advantages and overall national strength (Tu et al., 2023) (see Table 2). China's major science and technology projects are typically government-led and receive substantial capital investment. These projects are aligned with national strategies, emphasize independent innovation, and focus on integrating university-industry-research efforts to facilitate the transformation and application of scientific research outcomes (Shi et al., 2022). However, China still faces challenges such as insufficient innovation capacity and ineffective transformation of scientific and technological achievements. Examining China's major scientific and technological projects from the perspective of the innovation ecosystem helps to understand the internal operating mechanisms of the research system and promotes scientific and technological innovation, thereby enhancing the transformation of

Table 1
Comparison between the innovation system of national major science and technology projects and the natural ecosystem.

Ecology	Definition	Innovation ecosystem system of national major science and technology projects	Definition
Species	Biont	Major special innovation organization	Major innovation subjects and related subjects
Population	A collection of individuals of the same species	Innovative population	A collection of innovative individuals with the same resources and functions
Community	A collection of different biological populations	Innovation community	A collection of innovative populations
Gene	Genetic material for biological traits	Innovation convention	Innovative decision rules
Accommodate	Changes with the natural environment	Strain	Respond to changes in the innovation environment
Synergy	Species co-evolve by complementing each other	Synergy	Synergy of innovation elements
Mutualism	Bidirectional interest exchange mechanism between symbiotic units	Mutualism	Two-way flow mechanism between different innovation organizations
Producer	An organism that produces organic matter from inorganic matter	Innovative subject	Project implementers who create real productivity
Consumer	Organisms that consume organic matter produced by producers	Innovation user	The audience for the innovation results, including the project's supervisors
Ecological environment	The environment in which species live	Innovation environment	The environment that influences innovation activities
Stream	The connection between species	Stream	Information sharing and transmission among innovative individuals
Ecological system	A system of interaction between community and environment	Innovation ecosystem for major projects	Innovative system organization interacts with the environment

scientific and technological achievements.

Firstly, the innovation ecosystem of national major science and technology projects is a dynamic open system. It not only exhibits the general characteristics of an open system but also possesses unique traits specific to its nature.

- (1) Integrity: National science and technology major projects involve numerous stakeholders and knowledge-sharing platforms. These entities are interdependent, restrictive, and cooperative. The system is not a simple linear assemblage but a cohesive whole required to complete the project. The absence of any element within the system can compromise overall performance, as the system relies on the cooperation of all its components, with changes in cooperation affecting system performance.
- (2) Diversity: The structure of the innovation ecosystem for national major science and technology projects is diverse. Various interest groups must collaborate closely to optimize the overall function of the system's value chain. The degree of integration among system members directly influences the system's effective implementation efficiency.
- (3) Dynamics: There are dynamic interactions between nodes within the innovation ecosystem of national major science and technology projects and between the system and its environment. These interactions, facilitated by information flow, enable dynamic self-regulation to achieve balance within and outside the system (Zerjav, 2021).
- (4) Ecotype: The innovation population, innovation community, innovation chain, and innovation network formed within the innovation ecosystem of national major science and technology projects share significant similarities in form and function with biological populations, communities, food chains, and food webs

in natural ecosystems. The failure of synchronization and upgrade in any link of the chain network structure can disrupt the synchronization and upgrade of other related parts within the entire chain network structure.

- (5) Feedback: The system can adapt to changes in the external environment through a feedback adjustment mechanism, which characterizes the system's stability. Although the demand environment may fluctuate, the system's feedback adjustment mechanism enables all stakeholders to make necessary adjustments based on demand information, ensuring the completion of established tasks and achieving the system's innovation goals.
- (6) Learning: Unlike natural ecosystems, the innovation ecosystem of national major science and technology projects comprises various stakeholders with self-awareness and creativity. System members possess a certain level of wisdom that promotes ecosystem learning. Responsible groups must continuously share system information, accept new ideas, foster knowledge spillover, and drive knowledge renewal and execution improvement.

3. Structure of innovation ecosystem of national major science and technology projects

3.1. Constituent elements

Natural ecosystems are composed of biomes (biological components) and abiotic environments (non-biological components), further subdivided into producers, consumers, decomposers, and inorganic environments. In natural ecosystems, green plants are the predominant producers, utilizing photosynthesis and other inorganic substances to produce organic matter, thereby fixing environmental energy in the form of chemical energy within organic bodies, achieving autotrophic

Table 2
Characteristics of the innovation ecosystem of major national science and technology projects.

Characteristics	Contents
Integrity	The numerous stakeholders of major national science and technology projects are independent of each other but also restrict each other and cooperate with each other.
Diversity	Close cooperation between different interest groups to achieve overall functional optimization.
Dynamic nature	There is a dynamic interaction between the nodes of the innovation ecosystem and the environment of the system in order to achieve the balance between the inside and outside of the system.
Ecotype	The similarity between the innovation ecosystem of national science and technology major projects and the natural ecosystem.
Feedback	With the changes of the external environment, each stakeholder in the system makes corresponding adjustments.
Learning	Each theme of the national science and technology major special innovation ecosystem promotes knowledge update and execution through continuous learning.

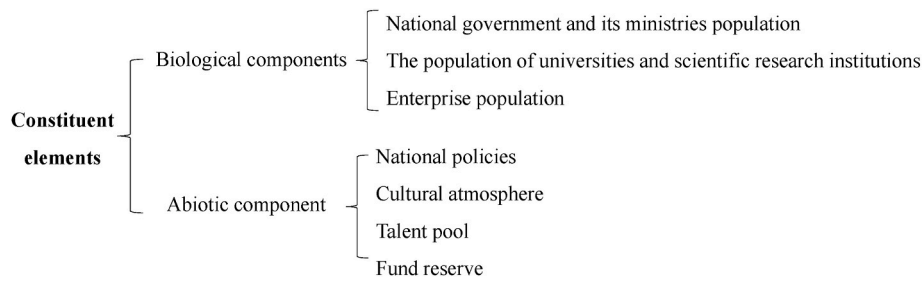


Fig. 1. Constituent element.

life. Consumers refer to heterotrophic organisms that directly or indirectly use the organic matter synthesized by green plants as food (Luo, 2010). Decomposers, mainly bacteria, fungi, and other microorganisms, as well as some invertebrates, utilize residues of animals and plants and organic matter in excrement for their life activities, gradually breaking down complex organic matter into simple inorganic substances. Biological communities and abiotic environments in natural ecosystems constitute biological and abiotic components, respectively. Similarly, the innovation ecosystem of national science and technology major projects in this study includes project innovation ecological communities and project innovation environments, which can also be regarded as biological and abiotic components (Fig. 1).

(1) Biological components

Innovation individuals: The innovation ecosystem comprises various individual subjects within the system, from the State Council and the Ministry of Science and Technology to universities and enterprises acting as project undertakers, forming the basic units of diverse innovation activities.

Innovation population: This term refers to collections of innovative individuals with similar functions and shared interests within the ecosystem. For example, all research institutions under the same subproject can form a research institution population.

Innovation community: This refers to the relative concentration of different innovation populations, representing the aggregation of each innovation population. These are not random combinations but must meet specific criteria: (a) each population should revolve around a specific element, such as innovation populations within the same subproject, (b) there are significant differences in activities and outputs among innovation groups and individuals within the community, and (c) the community's nature is defined by its members, structure, and organization, imposing mutual restrictions and cooperation among innovation entities (Huang, 2007).

The innovation ecological community of national major science and technology projects forms the system's biological component, including relevant innovation populations such as universities, scientific research institutions, the national government and its ministries and commissions, and enterprises (suppliers, competing enterprises, supporting enterprises, etc.).

a **National government and ministry population:** National major science and technology projects are under the unified leadership of the State Council. The Ministry of Science and Technology, along with the National Development and Reform Commission, the Ministry of Finance, and other relevant departments, establishes a leading group for these projects, responsible for overall planning and daily management. This group is divided into financial, administrative, and technical management groups. Though not directly completing major projects, these bodies play a crucial role in promoting and

coordinating information flow within the system, ensuring smooth project progress. They are the leading decision-makers, benefit sharers, and audiences who guide and supervise the projects while also consuming the research results.

b **Universities and scientific research institutions population:** National major science and technology projects are generally large-scale, broken into interrelated subtopics completed by various organizations, with universities and research institutions as the main undertakers. These institutions, being upstream in the innovation ecosystem, act as producers, providing high-quality innovation outcomes and promoting the transformation and industrialization of scientific research results through cooperation with enterprises.

c **Enterprise population:** Enterprises are vital participants in the innovation ecosystem, playing roles as producers, consumers, and decomposers. This includes supplier enterprises providing innovation resources, R&D enterprises, supporting enterprises driven by innovation, and audience enterprises benefiting from research transformations. Enterprises contribute to productivity using the latest research results and act as decomposers, processing and recycling waste materials generated during project implementation.

(2) Abiotic component

Innovation Environment: This encompasses the external conditions affecting the existence, development, and evolution of the innovation ecosystem. For national major science and technology projects, the innovation environment includes national policies, cultural atmosphere, talent pools, and capital reserves, constituting the abiotic components of the ecosystem.

a. **National policies:** These policies support scientific and technological activities through public policies aimed at ensuring the smooth declaration, implementation, and transformation of special projects. Policies include innovation supply-side policies (supporting human, material, financial, and technical resources), demand-side policies (government or regulatory body initiatives affecting project implementation), and environmental policies (laws and regulations).

b. **Cultural atmosphere:** This refers to the innovative values and behaviors formed over time by subjects within the innovation ecosystem, facilitating collaboration among different organizations and promoting overall progress and project completion.

c. **Talent pool:** The availability and quality of human resources determine the success of scientific research activities. An adequate and dynamic talent pool ensures the smooth execution of projects, while a conducive human resource environment enables effective interaction and collaboration within the ecosystem.

d. **Fund reserve:** Adequate funding is crucial for the progress of scientific research and innovation activities. National major

science and technology projects are primarily funded through government allocations, ensuring sufficient financial resources for project implementation.

The innovation community and environment together form a four-level structure of the innovation ecosystem for national major science and technology projects: the enterprise innovation layer (suppliers, R&D enterprises, supporting enterprises, and audience enterprises), the research core layer (universities and research institutions), the auxiliary innovation layer (government and ministries), and the external environment innovation layer (national policies, regulations, cultural atmosphere, talent pool, and fund reserves).

3.2. Interrelationship among components (four-level model)

(1) Enterprise innovation layer and research innovation layer

As the primary innovation agents in the ecosystem of national major science and technology projects, enterprises and universities, along with research institutions, collectively function as producers within the system. Their direct collaboration in frontier technology research and development significantly enhances the production of scientific research outputs. By leveraging their respective strengths, enterprises elevate their innovative research capacities through partnerships that capitalize on the academic expertise of universities and research institutions. Concurrently, the intellectual resources and human capital from these academic entities are further cultivated and utilized.

Additionally, science and technology parks located near universities and research institutions often attract numerous enterprises, or facilitate the establishment of high-tech startups by outstanding university talents. These enterprises, whether collaborating with or originating from academic institutions, contribute to the dynamic flow and effective integration of innovation resources within the ecosystem. This symbiotic relationship fosters the transformation and dissemination of scientific research innovations throughout the system.

(2) Auxiliary innovation layer, enterprise innovation layer, and research innovation layer

The government plays a crucial role in guiding and supporting the innovation activities of enterprises, universities, and research institutions. By formulating various promotion policies, the government accelerates the overall enhancement of scientific research and

innovation capabilities within the ecosystem. Through fiscal, tax, and local financial policies, the government and the leading group of national major science and technology projects provide subsidies and tax incentives to enterprises and individuals with strong innovative abilities and potential. These measures are designed to expedite the operation of innovation research and development within the system.

Additionally, the government exercises macro-control over the market environment to ensure fair competition in R&D and other innovative activities among enterprises. The government maintains close ties with universities and research institutions, encouraging their scientific research and innovation efforts through financial investments. These investments help address scientific research challenges and technical barriers, thereby enhancing the efficiency of research output.

Furthermore, universities and research institutions supply innovative talents necessary for the execution of major projects. By undertaking national major projects, these academic and research entities fulfill the government’s needs in specific innovation directions, thereby ensuring a continuous flow of talent and innovation to support national strategic goals.

(3) External environment innovation layer and other layers

The external environment innovation layer of national major science and technology projects is closely interconnected with the enterprise innovation layer, the scientific research innovation layer, and the auxiliary innovation layer. The actions of the innovation entities within the system facilitate the development of the innovation environment. National policies, formulated and promoted by the government, along with the system’s rules and regulations, provide robust support and assurance for the government, enterprises, universities, and research institutions to conduct innovative scientific research activities and exchange information.

The innovation mindset and atmosphere among these entities significantly influence the system’s social and cultural environment. The scientific research activities and outputs from enterprises and university research institutions strongly support the national fund reserve and contribute to the development of a new pool of outstanding talents.

Thus, the relationships among the elements that constitute the innovation ecosystem of national major science and technology projects are complex and intertwined. These relationships form a four-level structural model of the innovation ecosystem, as illustrated below (see Fig. 2).

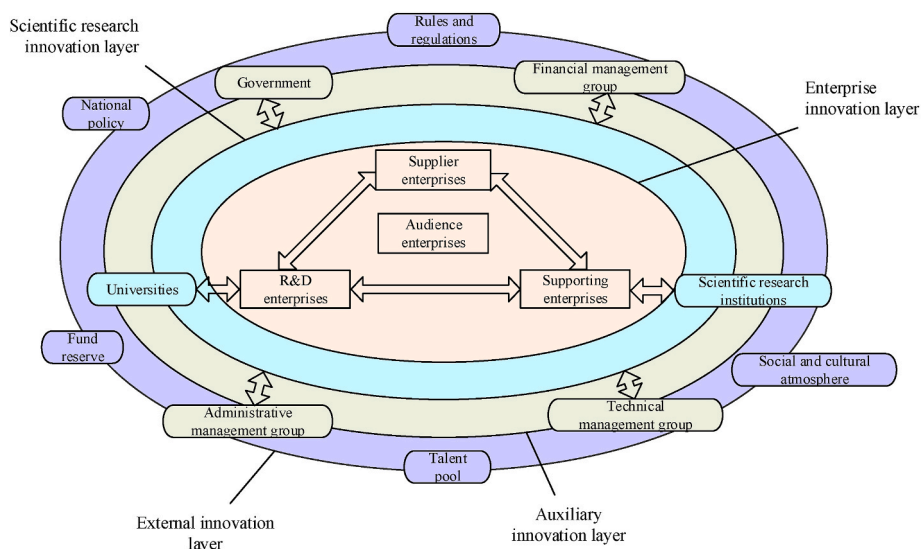


Fig. 2. The interrelationship diagram of the constituent elements of the innovation ecosystem of national major science and technology projects.

4. The operation mechanism of the innovation ecosystem of national major science and technology projects

Analogous to biological populations in natural ecosystems, the innovative entities within the innovation ecosystem of national major science and technology projects do not exist in isolation. Within a given environment, various groups in the system interact, leading to the flow of innovative resources and the formation of complex relationships among these groups. These relationships encompass both competition and cooperation.

In the national major innovation ecosystem, mechanisms of competition, cooperation, and sharing are interdependent and critical for promoting scientific and technological innovation and development. The competition mechanism stimulates innovation among different entities, fostering the continuous emergence and improvement of technological achievements. The cooperation mechanism enhances the connections and collaborations among innovation subjects, providing a broad platform for cross-field and cross-industry scientific and technological innovation. The sharing mechanism facilitates resource sharing and the widespread application of technological achievements through open access to research data, shared R&D facilities, and platforms for the transformation of scientific and technological results. By analyzing the operation of these mechanisms, we can gain a deeper understanding of the functioning and impact of the national major innovation ecosystem. The interaction of these mechanisms not only drives the process of technological innovation but also promotes the transformation and application of scientific achievements, contributing significantly to the continuous enhancement of national scientific and technological capabilities.

This paper employs the Lotka-Volterra competition model to study the competitive symbiosis mechanism within the innovation ecosystem of national major science and technology projects. By combining qualitative and quantitative methods, it examines the collaborative mechanisms across three dimensions: knowledge, scientific research, and benefits. Knowledge synergy promotes the circulation of cutting-edge knowledge, scientific research synergy facilitates the transformation of results, and benefit synergy achieves win-win outcomes. Establishing knowledge and benefit sharing mechanisms enables cooperation and coordination among all parties, fostering the smooth progress of scientific and technological innovation.

4.1. Competitive symbiosis mechanism

Within the innovation ecosystem of China's major science and technology projects, the mechanisms of competitive symbiosis and collaboration coexist in a way that strengthens both, enhancing the ecosystem's vitality and resilience. Competitive symbiosis acts as a catalyst, encouraging healthy competition among innovation actors, which drives continuous improvements, technological progress, and advancements. On the other hand, collaboration is crucial for fostering mutual benefits and symbiotic relationships, facilitating the removal of barriers, and promoting the sharing of resources, information, and expertise. This, in turn, enables the realization of complementary strengths and joint innovation efforts.

A deep understanding of the complex interaction between competitive symbiosis and collaboration is essential for advancing the high-quality development of the national innovation ecosystem. This insight enhances the ecosystem's resilience and competitiveness in the face of domestic and international challenges, providing a solid foundation and assurance for sustainable, high-quality development (Han et al., 2024).

4.1.1. Competition model

Competition refers to the negative interaction between organisms when they vie for the same resources (Odum et al., 2009). Consequently, two populations cannot occupy the same ecological niche (the role and

position a species has in its environment) simultaneously. They must adapt their resource utilization or lifestyle to gain comparative advantages, thus avoiding niche overlap. Similarly, competition plays a vital role in the innovation ecosystem of national major science and technology projects. Although competition may negatively affect a particular population, this impact is not necessarily detrimental. While competition can reduce the population growth rate, it does not hinder long-term survival. In fact, competition can stimulate selective adaptations in populations, enhancing the coexistence of diverse populations within the innovation ecosystem.

Lotka and Volterra developed the renowned Lotka-Volterra competition model to analyze interspecies competition. The model, which incorporates factors such as resource competition, population growth, and population density, aptly describes the competitive relationships within the national science and technology innovation ecosystem. The Lotka-Volterra competition model is a classical ecological model used to depict competition between two species sharing a common resource environment (Zhao and Yuan, 2022). The model is often generalized to accommodate multi-species competition. This paper uses the model to analyze the survival dynamics of competing populations. The competition equations for any two competing innovative populations in the system are as follows:

$$\frac{dP_1}{dt} = i_1 P_1 \frac{(L_1 - P_1 - c_{12}P_2)}{L_1} \quad (1)$$

$$\frac{dP_2}{dt} = i_2 P_2 \frac{(L_2 - P_2 - c_{21}P_1)}{L_2} \quad (2)$$

Where: c_{12} and c_{21} represent the competition coefficients, L_1 and L_2 represent the carrying capacities of populations 1 and 2, P_1 and P_2 denote the sizes of the two populations, and i_1 and i_2 are the maximum intrinsic growth rates of the populations.

The above model demonstrates that the growth rate of competing populations varies with changes in population size. To determine the ecological equilibrium of the ecosystem, we analyze the isoclines of the two populations, setting $dP_1/dt = dP_2/dt = 0$. When equations (1) and (2) are set to zero, a stable state is achieved:

$$P_1 = L_1 - c_{12}P_2 \quad (3)$$

$$P_2 = L_2 - c_{21}P_1 \quad (4)$$

The coordinates of the stable point can be determined as $P_1^* = \frac{L_1 - c_{12}L_2}{1 - c_{12}c_{21}}$, $P_2^* = \frac{L_2 - c_{21}L_1}{1 - c_{12}c_{21}}$. Below the isocline, the population will decrease. Coexistence between the two populations is possible only if the intensity of intraspecific competition is greater than the intensity of interspecific competition. In other words, when a population's self-inhibition is stronger than the inhibition imposed by the other population, stable coexistence can be achieved. Mathematically, this condition is expressed as $L_1 < L_2/c_{21}$ and $L_2 < L_1/c_{12}$. The competition dynamics between the two populations are illustrated below:

In Fig. 3(a), L_1 represents the environmental carrying capacity of population 1, indicating that in the absence of population 2, population 1 will continue to grow until $dP_1/dt = 0$. The term L_2/c_{21} represents the intersection of the isocline of population 2 with the P_1 -axis, signifying the size of population 1 when $dP_1/dt = 0$ and population 2 has reached its growth limit. Here, $L_2/c_{21} < L_1$ but $L_1/c_{12} > L_2$, meaning that population 1 continues to grow while population 2 ceases to grow. Consequently, in competition between these two species, population 1 always prevails. Conversely, Fig. 3(b) demonstrates that population 2 consistently wins in competitive interactions.

In Fig. 3(c), below the intersection point, the intersection of the isocline of population 2 with the P_1 -axis is L_2/c_{21} , indicating that when the size of population 2 is zero, population 1 equals L_2/c_{21} . The environmental carrying capacity of population 1 is L_1 , and since $L_2/c_{21} < L_1$, population 1 prevails and increases in number below the intersection, while population 2 diminishes. Conversely, above the intersection, the

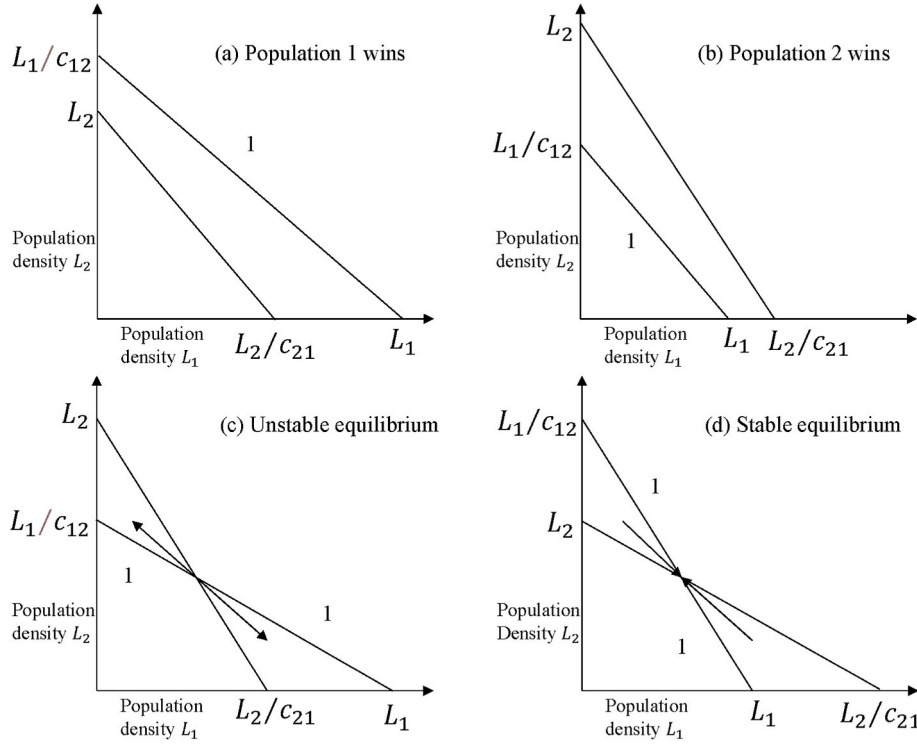


Fig. 3. Four potential representations of the competitive model.

outcome of competition between the two populations is uncertain, and regardless of which population wins, the system moves away from equilibrium. Thus, this scenario is termed unstable equilibrium.

In Fig. 3(d) below the intersection, population 2 wins. Following this victory, the number of population 2 continues to increase while population 1 decreases, gradually shifting the population dynamics towards and above the intersection point. Similarly, if population 1 wins, the system gradually moves towards the intersection. In this case, the populations oscillate above and below the intersection, ultimately reaching a stable equilibrium.

In real-world ecosystems, competition often involves more than two species. The Lotka-Volterra competition model can be extended to:

$$\frac{dP_\alpha}{dt} = i_\alpha \cdot P_\alpha \left[\frac{L_\alpha - P_\alpha - \left(\sum_{\beta \neq \alpha}^n c_{\alpha\beta} P_\beta \right)}{L_\alpha} \right] \quad (5)$$

At equilibrium, for all species α , $dP_\alpha/dt = 0$, and

$$P_\alpha = L_\alpha - \left(\sum_{\beta \neq \alpha}^n c_{\alpha\beta} P_\beta \right) \quad (\alpha = 1, 2, \dots, n) \quad (6)$$

When multiple populations compete simultaneously, the system's dynamics become complex. Equilibrium is achieved when intraspecific competition exceeds interspecific competition, allowing each pair of populations to coexist in the absence of others. The equilibrium point lies in the plane defined by the environmental carrying capacities of the populations. Similarly, more than three species can compete and achieve equilibrium under these conditions.

4.1.2. Symbiosis model

In nature, ecosystems often exhibit symbiotic relationships. This concept also applies to the innovation ecosystem of national major science and technology projects, where mutual cooperation among innovation groups enhances project success rates, shortens implementation durations, and reduces costs and risks. In cooperative interactions

between two innovative populations, relationships may manifest as parasitism, favoritism, mutualism, or independent coexistence.

In the innovation ecosystem of national projects, parasitism refers to an interaction where one population benefits at the expense of another. Typically, a dominant population in terms of technology or market control forms a parasitic relationship with a weaker population that relies on the former for survival. Over time, the weaker population may accumulate resources and evolve into a mutually beneficial partner or an independent entity. Alternatively, the parasitic relationship may deteriorate, leading to the weaker population's decline.

Mutualism describes a relationship where both populations benefit and depend on each other. This positive interaction fosters win-win outcomes through resource integration and complementary advantages. In national science and technology ecosystems, mutualism is common among enterprises, universities, and research institutions engaged in collaborative innovation and technology transfer. Favoritism, on the other hand, is a positive interaction that benefits the growth or survival of one innovative population while having a lesser impact on the other. Unlike mutualism, the benefit of favoritism is unidirectional.

The symbiosis of innovative populations can be modeled by modifying the Lotka-Volterra competition equation's interaction term:

$$\frac{dP_1}{dt} = i_1 \cdot P_1 \frac{(L_1 - P_1 + s_{12}P_2)}{L_1} \quad (7)$$

$$\frac{dP_2}{dt} = i_2 \cdot P_2 \frac{(L_2 - P_2 + s_{21}P_1)}{L_2} \quad (8)$$

When equations (7) and (8) converge to zero, they establish a stable equilibrium between populations:

$$P_1 = L_1 + s_{12}P_2 \quad (9)$$

$$P_2 = L_2 + s_{21}P_1 \quad (10)$$

The stable point coordinates are determined as $P_1 = \frac{L_1 + s_{12}L_2}{1 - s_{12}s_{21}}$ and $P_2 = \frac{L_2 + s_{21}L_1}{1 - s_{12}s_{21}}$. The potential symbiotic relationship between the two

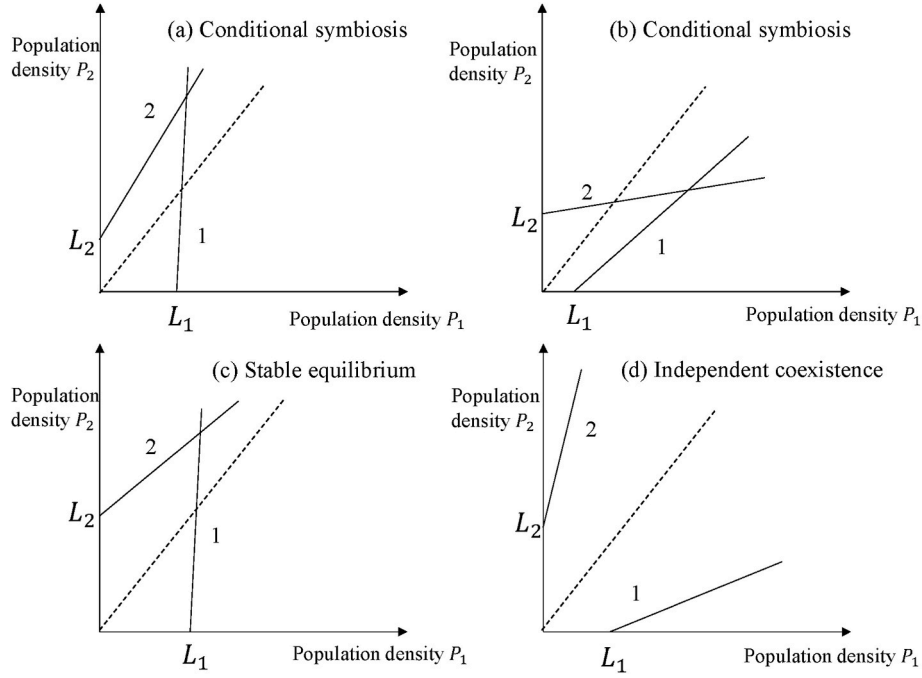


Fig. 4. Four possible scenarios for the symbiosis model.

populations is illustrated in the following figure:

In Fig. 4(a), where $s_{12} < 1$ and $s_{21} > 1$, the two populations may exhibit conditional symbiosis. When the growth curves of the two populations intersect, a symbiotic equilibrium point is established. The condition for achieving this equilibrium is that the slope of the growth curve of population 1 is greater than that of population 2, expressed as $1/s_{12} > s_{21}$ or $s_{12}s_{21} < 1$. Similarly, in Fig. 4(b), where $s_{12} > 1$ and $s_{21} < 1$, the condition for stable coexistence is also $1/s_{12} > s_{21}$ or $s_{12}s_{21} < 1$. In both scenarios, there is a significant disparity in the symbiotic capacities of the populations. The population with stronger symbiosis capability will develop rapidly, whereas the one with weaker symbiosis capability will exhibit minimal growth and change. This situation is termed favorable symbiosis. If neither population significantly benefits, it is considered parasitism. To achieve a symbiotic equilibrium, the condition $s_{12}s_{21} < 1$ must be satisfied.

In Fig. 4(c), where $s_{12} < 1$ and $s_{21} < 1$, the populations exhibit mutualistic symbiosis. Here, both populations have similar symbiotic capabilities and are inclined to actively form a symbiotic relationship. This relationship is stable and positively impacts both populations, leading to the formation of a stable equilibrium point and balanced development of both populations.

In Fig. 4(d), where $s_{12} > 1$ and $s_{21} > 1$, the strong independence of the two populations hinders the formation of a symbiotic equilibrium, a scenario that is rarely observed in reality.

4.1.3. Competition and cooperation model

Competition and cooperation often coexist within ecosystems. By integrating the above models, we obtain the following combined model. Here, γ represents the coefficient that quantifies the balance between competition and symbiosis between two populations. A positive γ indicates that competition predominates the interaction, whereas a negative γ signifies that symbiosis is the dominant interaction. The model is expressed as follows:

$$\frac{dP_1}{dt} = i_1 \cdot P_1 \frac{(L_1 - P_1 - \gamma_{12}P_2)}{L_1} \quad (11)$$

$$\frac{dP_2}{dt} = i_2 \cdot P_2 \frac{(L_2 - P_2 - \gamma_{21}P_1)}{L_2} \quad (12)$$

The discrete form of equation (11) is given by:

$$P_{1(t+1)} - P_{1(t)} = \theta_1 P_{1(t)} - \frac{\theta_1 P_{1(t)}^2}{L_1} - \frac{\theta_1 \gamma_{12} P_{1(t)} P_{2(t)}}{L_1} \quad (13)$$

The relationship between the two populations can be expressed as:

$$P_1 = \gamma_{12} P_2 \quad P_2 = \gamma_{21} P_1 \quad (14)$$

Substituting equation (14) into equation (13), we obtain:

$$\Delta P_1 = \theta_1 \gamma_{12} P_{2(t)} - \frac{2\theta_1 \gamma_{12}^2 P_{2(t)}^2}{L_1} \quad (15)$$

Let $\Gamma_1 = \theta_1 \gamma_{12}$ and $\Gamma_2 = -2\theta_1 \gamma_{12}^2 / L_1$, then we have

$$\Delta P_1 = \Gamma_1 P_{2(t)} + \Gamma_2 P_{2(t)}^2 \quad (16)$$

The general form of this equation is:

$$\Delta P_1 = \Gamma_0 + \Gamma_1 P_{2(t)} + \Gamma_2 P_{2(t)}^2 + e(t) \quad (17)$$

The solution to this equation is:

$$P_2^* = \frac{-\Gamma_1 \pm \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_2}}{2\Gamma_2}$$

When $\Gamma_1 > 0$ and $\Gamma_2 > 0$, if there is no solution to the equation, the populations exhibit a symbiotic relationship. If a solution exists, when $P_2 > \frac{-\Gamma_1 + \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_2}}{2\Gamma_2}$, the interactions between populations primarily symbiotic. Conversely, when $0 < P_2 < \frac{-\Gamma_1 + \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_2}}{2\Gamma_2}$, competition is the dominant factor.

When $\Gamma_1 < 0$ and $\Gamma_2 > 0$, if there is no solution, the populations are symbiotic. If a solution exists, when $0 < P_2 < \frac{-\Gamma_1 - \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_2}}{2\Gamma_2}$ or $P_2 > \frac{-\Gamma_1 + \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_2}}{2\Gamma_2}$, the interactions are mainly symbiotic. While $\frac{-\Gamma_1 - \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_2}}{2\Gamma_2} < P_2 < \frac{-\Gamma_1 + \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_2}}{2\Gamma_2}$, competition is predominant.

When $\Gamma_1 > 0$ and $\Gamma_2 < 0$, if there is no solution, the relationship is competitive. If a solution exists and $\frac{-\Gamma_1 - \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_2}}{2\Gamma_2} < P_2 < \frac{-\Gamma_1 + \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_2}}{2\Gamma_2}$, the interactions are mainly symbiotic. Conversely, when $0 < P_2 <$

$\frac{-\Gamma_1 - \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_1}}{2\Gamma_2}$ or $P_2 > \frac{-\Gamma_1 + \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_1}}{2\Gamma_2}$, competition dominates.

When $\Gamma_1 < 0$ and $\Gamma_2 < 0$, if there is no solution, the populations are in competition. If a solution exists and $0 < P_2 < \frac{-\Gamma_1 + \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_1}}{2\Gamma_2}$, the interaction is dominated by competition. When $P_2 > \frac{-\Gamma_1 + \sqrt{\Gamma_1^2 - 4\Gamma_0\Gamma_1}}{2\Gamma_2}$, the interpopulation becomes mainly symbiotic.

Similarly, the change in P_2 is given by:

$$\Delta P_2 = \Gamma_0' + \Gamma_3 P_{1(t)} + \Gamma_4 P_{1(t)}^2 + e'_{(t)} \quad (18)$$

Here, $\Gamma_3 = \theta_2 \gamma_{21}$ and $\Gamma_4 = -2\theta_2 \gamma_{21}^2 / L_2$. Assuming $L_1 = L_2$, we obtain: $\frac{\Gamma_2}{\Gamma_4} = \frac{\theta_1 \gamma_{12}^2 K_2}{\theta_2 \gamma_{21}^2 K_1} = \frac{\Gamma_1 \gamma_{12}}{\Gamma_3 \gamma_{21}}$.

Substituting the expressions for $\Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4$, we get $\frac{\Gamma_2}{\Gamma_4} = \frac{\Gamma_2 \Gamma_3}{\Gamma_1 \Gamma_4}$. This indicates that the nature of competition or symbiosis between populations is primarily influenced by the competition or symbiosis coefficients. The parameters in the Lotka-Volterra model can be adjusted according to the ratio of the competition coefficients. In the innovation ecosystem of major national science and technology projects, both competition and symbiosis coexist and can transform into one another. The synergy between these interactions acts as a catalyst, promoting the system's operation. Innovative populations can seek symbiosis through competition, and symbiotic relationships may form in this process. Members of symbiotic groups can share risks, effectively reducing project risks and promoting project progress.

4.2. Coordination mechanism

Coordination refers to the alignment and synchronization between various elements. In the innovation ecosystem of national major science and technology projects, the coordination mechanism involves the orderly interaction between multiple project populations and communities. This interaction reduces transaction costs between groups, minimizes opportunistic behaviors, facilitates information sharing, promotes scientific and technological innovation, and enables risk sharing. Such a mechanism addresses the risks associated with scientific research and innovation during project implementation, enhancing cooperation and communication between communities.

The driving forces of the innovation ecosystem in national major science and technology projects include both internal and external factors. Internally, the driving forces encompass research capabilities, learning abilities, knowledge accumulation, creativity, and benefit-sharing abilities. Externally, they include national policies, institutional environments, social and cultural atmospheres, and national demands. Thus, the dynamic system of the innovation ecosystem comprises knowledge dynamics, scientific research innovation dynamics, relational dynamics, and benefit dynamics. Knowledge dynamics, the core driver for achieving research goals, arise from the learning abilities and knowledge accumulation within the system. Scientific research and innovation dynamics stem from the collective scientific research and innovation activities that propel the ecosystem, driven by factors such as research strength, national policies, institutional environment innovations, cultural innovations, and national demands. Benefit dynamics arise from the creation and benefit acquisition capabilities within the system. Based on the analysis of these dynamic factors, the coordination mechanism of the innovation ecosystem in national major science and technology projects includes three dimensions: knowledge coordination mechanism, scientific research and innovation coordination mechanism, and benefit coordination mechanism.

4.2.1. Knowledge collaboration mechanism

The knowledge coordination mechanism in the innovation ecosystem of national major science and technology projects pertains to the relationships among various components of the knowledge system, with scientific research and innovation at its core. It encompasses the

rules of knowledge interaction among population nodes and knowledge sources within the ecosystem (Aagaard and Rezac, 2022). Given the novelty of national major science and technology projects, the interactive knowledge is predominantly at the frontier of science and technology. The components of the knowledge coordination mechanism include knowledge sources, knowledge and technical means, and various operational platforms that ensure collaborative knowledge operation. Knowledge sources consist of cutting-edge scientific and technological knowledge reserves, supply populations, knowledge demand populations, and research and application populations that convert knowledge into productivity. Knowledge includes explicit and implicit knowledge, knowledge coordination mechanisms, knowledge transfer mechanisms, and knowledge sharing mechanisms (Gossain, 2002).

The knowledge coordination mechanism within the ecosystem promotes the circulation and diffusion of cutting-edge scientific and technological knowledge. The rich and dense knowledge generates spillover and sharing effects through the coordination mechanism, facilitating the overflow and spread of knowledge resources among various groups within the ecosystem.

4.2.2. Collaborative mechanism of scientific research and innovation

The collaborative mechanism of scientific research and innovation in the innovation ecosystem of national major science and technology projects refers to the interaction between various adaptive scientific research and innovation activities and the elements of the ecological environment during the stages of project establishment, planning, implementation, acceptance, and transformation. It involves the synthesis of scientific research and innovation driving forces and their interaction with the external environment. Its essence is to promote the flow of knowledge and resources within the ecosystem, achieve high-quality research outcomes, and benefit the public. The collaborative mechanism includes parallel processing of all stages in the scientific research and innovation process, collaboration among research and innovation groups such as enterprises, universities, and research institutions, and collaboration among various elements of scientific research and innovation, including policies, demands, and knowledge.

4.2.3. Benefit coordination mechanism

The benefit coordination mechanism in the innovation ecosystem of national major science and technology projects refers to the mechanisms for the equitable distribution or utilization of project research outcomes among various organizational platforms within the system. The core aim is to achieve win-win and benefit-sharing outcomes for all stakeholders, implementing the concept of collective benefit throughout the system. The benefit coordination mechanism comprises innovative interest subjects, benefit distribution elements, benefit distribution plans and principles, distributable results, and various supporting facilities.

4.3. Sharing mechanism

4.3.1. Knowledge sharing mechanism

The knowledge sharing mechanism in the innovation ecosystem of national major science and technology projects involves the maximum disclosure of internal information and knowledge, ensuring that special knowledge secrets are protected and the organizational platform's operation is secure. This mechanism ensures the comprehensive utilization of organizational knowledge.

The knowledge sharing mechanism is systematic, covering four aspects: cooperation, communication, transfer, and trust mechanisms. These aspects are integrated with the knowledge sharing process, enhancing efficiency and effectiveness in knowledge transfer and utilization. Cooperation mechanisms involve establishing cooperative relationships among stakeholders, centered on scientific research and innovation, and forming dynamic cooperation with enterprise and auxiliary innovation layers. Communication mechanisms involve

creating interactive communication frameworks among various innovation entities, with research institutions at the core, to facilitate knowledge sharing. Transfer mechanisms employ encoding and personalization strategies, utilizing tools like email, online meetings, and learning maps for knowledge transfer (Besen, 1995). Trust mechanisms underpin the entire knowledge sharing process, crucially influencing its frequency and depth. Establishing trust involves both systemic and cultural aspects within the ecosystem, fostering values and behaviors conducive to knowledge sharing.

4.3.2. Benefit sharing mechanism

The benefit-sharing mechanism in the innovation ecosystem of national major science and technology projects is realized through interest coordination. Interest coordination recognizes the legitimacy of various organizations' interests within the ecosystem, either increasing the supply of interest objects through scientific and technological means or maintaining rationality within a certain limit through institutionalized contracts. It involves conscious adjustments of interest concepts, behaviors, and mutual relations to achieve coordination goals (Cao et al., 2024). The benefit-sharing mechanism includes the community of interests, interest coordination mechanism, and interest conflict resolution mechanism. The community of interests involves stakeholders establishing clear agreements on interest sharing and risk-bearing through formal or informal consultations. The interest coordination mechanism adheres to the concept of collective benefit, identifying common and specific interests to integrate them and ensure reasonable benefit sharing among stakeholders. The interest conflict resolution mechanism addresses non-confrontational interest conflicts through dialogue and consultation, improving the interest distribution mechanism and adjusting the interest structure to mitigate opportunistic behaviors and reduce dependency and integration risks.

4.3.3. Information sharing mechanism

The information sharing mechanism in the innovation ecosystem of national major science and technology projects guarantees the establishment of information-sharing platforms, creating a conducive sharing atmosphere and facilitating information exchange among innovation groups during scientific and technological innovation activities. Establishing information platforms helps collect necessary information for stakeholders and promotes knowledge flow and transfer among individuals, forming the basis of interactive learning within the innovation ecosystem. Creating a sharing atmosphere is essential for establishing trust mechanisms among populations, enhancing the ecosystem's openness and flexibility. The operational guarantee mechanism includes systems, organizational input, and technical support, utilizing both software (systems and culture) and hardware (high-tech achievements like computers, networks, and wireless equipment) to ensure effective information sharing.

5. Conclusion

This study, based on ecological and system science theories, examines the innovation ecosystem of national major science and technology projects. By comparing the components of this innovation ecosystem with natural ecosystems, we analyze major science and technology projects in China from an innovation ecosystem perspective. We identify the characteristics of the national science and technology major special innovation ecosystem and construct the corresponding system structure. Further, we discuss the competition and symbiosis mechanisms, coordination mechanisms, and sharing mechanisms within the system, providing new insights for research on national science and technology major projects.

Applying the concept of natural ecosystems to national science and technology major projects, this paper reveals the theoretical framework and operational mechanisms of the innovation ecosystem in China. This provides valuable insights for better management and promotion of

project implementation. However, due to the unique strategic orientation and international cooperation characteristics of China's major science and technology projects, this study focuses on China rather than other countries. This limitation is also a focus for future research.

CRediT authorship contribution statement

Kun Wang: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Yu Feng:** Writing – review & editing, Writing – original draft. **Siyao Liu:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Acknowledgments

This work was supported by the National Social Science Fund of China [grant number 22&ZD135].

References

- Aagaard, A., Rezac, F., 2022. Governing the interplay of inter-organizational relationship mechanisms in open innovation projects across ecosystems. *Ind. Market. Manag.* 105, 131–146.
- Adner, R., 2006. Match your innovation strategy to your innovation ecosystem. *Harv. Bus. Rev.* 84 (4), 98–107.
- Adner, R., 2017. Ecosystem as structure: an actionable construct for strategy. *J. Manag.* 43 (1), 39–58.
- Besen, 1995. Explaining development and change in Organization. *Academy of Manag. Rev.* 1995 (20), 510–540.
- Brem, A., Nylund, P., 2022. The inertia of dominant designs in technological innovation: an ecosystem view of standardization. *IEEE Trans. Eng. Manag.* 71, 2640–2648.
- Cao, M., Chiclana, F., Liu, Y., Wu, J., Herrera-Viedma, E., 2024. A bilateral negotiation mechanism by dynamic harmony threshold for group consensus decision making. *Eng. Appl. Artif. Intell.* 133, 108225.
- Dai, L., Liao, H., Luo, S., Sun, Y., 2024. Strengthening enterprise-led deep integration of industry, University and research: perspective of executive academic experience. *Sci. Res.* 1–20.
- Daniel, E., Daniel, P.A., 2019. Megaprojects as complex adaptive systems: the Hinkley point C case. *Int. J. Proj. Manag.* 37 (8), 1017–1033.
- Davies, R.M.G., Saunders, R.G., 1988. Applying systems theory to project management problems. *Int. J. Proj. Manag.* 6 (1), 19–26.
- Feng, T., Zhu, Z., 2024. Heterogeneity government subsidies influence on enterprise resilience research. *Journal of southwest university (social science edition)* 50 (1), 144–155.
- Flyvbjerg, B., 2014. What you should know about megaprojects and why: an overview. *Proj. Manag. J.* 45 (2), 6–19.
- Fuller, J., Jacobides, M.G., Reeves, M., 2019. The myths and realities of business ecosystems. *MIT Sloan Manag. Rev.* 60 (3), 1–9.
- Gossain, S., 2002. Cracking the collaboration code. *J. Bus. Strat.* 23 (6), 20–25.
- Guo, Y., Xie, W., Yang, Y., 2024. Dual green innovation capability, environmental regulation intensity, and high-quality economic development in China: can green and growth go together? *Finance Res. Lett.* 63, 105275.
- Han, Y., Yang, Q., Tian, P., 2024. The fundamentals of boosting high-quality development by megaprojects: a systematic literature review. *Project Leadership and Society*, 100140.
- Huang, L., 2007. *Research on Technological Innovation Behavior Based on Ecology*. Science Press, Beijing.
- Jin, Z., Zeng, S., Chen, H., Shi, J., 2022. Creating value from diverse knowledge in megaproject innovation ecosystems. *Int. J. Proj. Manag.* 40 (6), 646–657.
- Jin, S., Wu, L., Xue, Z., Geng, X., 2023. School-enterprise cooperation, Firm innovation and firm value: new evidence from high-tech industry. *The southern economy* 10, 127–144.
- Kapsali, M., 2011. Systems thinking in innovation project management: a match that works. *Int. J. Proj. Manag.* 29 (4), 396–407.
- Lehtinen, J., Peltokorpi, A., Artto, K., 2019. Megaprojects as organizational platforms and technology platforms for value creation. *Int. J. Proj. Manag.* 37 (1), 43–58.

- Li, W., 2008. Study on Regional Innovation System Based on Evolutionary Theory. Doctoral Dissertation of Tianjin University, Tianjin.
- Love, P.E., Edwards, D.J., Irani, Z., 2011. Moving beyond optimism bias and strategic misrepresentation: an explanation for social infrastructure project cost overruns. *IEEE Trans. Eng. Manag.* 59 (4), 560–571.
- Luo, Y., 2010. Research on Performance Evaluation of Regional Technological Innovation Ecosystem. Economic Science Press, Beijing.
- Malherbe, M., 2022. Cooperating in interorganizational innovation projects: toward a better understanding of coupling with the permanent ecosystem. *Int. J. Proj. Manag.* 40 (8), 871–885.
- Odum, Barret, Lu, Jian, 2009. Basis of Ecology. Higher Education Press, Beijing et al.
- Paasi, J., Wiman, H., Apilo, T., Valkokari, K., 2023. Modeling the dynamics of innovation ecosystems. *International Journal of Innovation Studies* 7 (2), 142–158.
- Peng, J., Bao, L., 2023. Construction of enterprise business management analysis framework based on big data technology. *Heliyon* 9 (6), e17144.
- Shi, Z., Wu, Y., Chiu, Y.H., Chang, T.H., 2022. Research on the influence of technological innovation and technological application: evidence from China. *J. Eng. Technol. Manag.* 63, 101670.
- Silvius, G., Marnewick, C., 2022. Interlinking sustainability in organizational strategy, project portfolio management and project management a conceptual framework. *Procedia Comput. Sci.* 196, 938–947.
- Theodoraki, C., Catanzaro, A., 2022. Widening the borders of entrepreneurial ecosystem through the international lens. *J. Technol. Tran.* 47 (2), 383–406.
- Tu, W., Zhang, L., Sun, D., Mao, W., 2023. Evaluating high-tech industries' technological innovation capability and spatial pattern evolution characteristics: evidence from China. *Journal of Innovation & Knowledge* 8 (1), 100287.
- Wang, X., Zhao, M., Zhang, S., Chen, M., 2023. Research on the asymmetrical effect of government funding structure on university research innovation. *Science and Technology Management Research* 43 (1), 43–52.
- Xu, Y., Sun, H., Lyu, X., 2023. Analysis of decision-making for value co-creation in digital innovation systems: an evolutionary game model of complex networks. *Manag. Decis. Econ.* 44 (5), 2869–2884.
- Yang, I.T., 2007. Performing complex project crashing analysis with aid of particle swarm optimization algorithm. *Int. J. Proj. Manag.* 25 (6), 637–646.
- Zeng, J., Chen, X., Liu, Y., Cui, R., Zhao, P., 2022. How does the enterprise green innovation ecosystem collaborative evolve? Evidence from China. *J. Clean. Prod.* 375, 134181.
- Zerjav, V., 2021. Why do business organizations participate in projects? Toward a typology of project value domains. *Proj. Manag. J.* 52 (3), 287–297.
- Zhao, J., 2024. How do innovation factor allocation and institutional environment affect high-quality economic development? Evidence from China. *Journal of Innovation & Knowledge* 9 (2), 100475.
- Zhao, X., Yuan, R., 2022. Propagation dynamics of a Lotka–Volterra competition model with stage structure in time–space periodic environment. *Nonlinear Anal. R. World Appl.* 67, 103575.