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The science-policy interface of ecological governance: functions, risks, and practices of boundary objects in China

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Effective interactions between science and policy are essential for sustainable development in ecological governance. Boundary objects connect heterogeneous communities and facilitate knowledge integration, providing a unique perspective for understanding the science-policy interface (SPI). However, a systematic understanding of their functions, mechanisms, and dual-sided effects is lacking. This paper constructs an integrated "function-mechanism-effect" analytical framework to systematically examine boundary objects. It explores their theoretical connotations and multidimensional functions in SPI, examines their action mechanisms, and dialectically assesses their positive effects as "glue" and potential risks as "blindfolds." The paper analyzes typical boundary objects in China's ecological governance, including the "ecological protection red line," the "mountains, waters, forests, lakes, grasses, and sands" system, and the "two mountains theory," while also exploring emerging tools like GEP accounting. Through a comparative analysis, the study reveals how these cases form a complementary "governance tools matrix," demonstrating their complex operations and inherent risks. The findings refine boundary object theory and offer practical guidance for the prudent design and "life-cycle management" of these tools, aiming to foster more inclusive and adaptive governance models.

KEYWORDS

boundary objects, eco-governance, eco-indicators, knowledge co-production, science-policy interface, the case of China

1 Introduction

The complexity and urgency of global environmental problems present a serious challenge to traditional linear governance models (Hering, 2016). Translating scientific knowledge into policy action is a central topic in sustainability science (Norström et al., 2020; Käyhkö et al., 2025). The efficiency of the Science-Policy Interface (SPI) is critical to environmental governance. As a key field linking knowledge production and decision-making, the success or failure of the SPI will directly impact environmental governance outcomes (Watson, 2005). However, significant differences in language paradigms, value pursuits, time scales, and incentives between the scientific and policy communities create what can seem like an unbridgeable chasm between these two fields (Carlile, 2004; Chong et al., 2017; Dinesh et al., 2021; Fähnrich and Ruser, 2019).

To cross this chasm, academics and practitioners have developed a variety of theories and tools. Among these, the concept of the boundary object, introduced by Star and Griesemer (1989), is particularly prominent. They defined it as an item possessing both interpretive flexibility and structural robustness, a duality that allows diverse groups to collaborate around a common referent without first achieving consensus. In the context of the SPI, examples of boundary objects are well-documented: they can be are specific models (Chong et al., 2017), policy-relevant communication outputs (Cvitanovic et al., 2025), ecological indicators (McCool and Stankey, 2004), or even shared vocabularies or conceptual frameworks (Nesshöver et al., 2017). They facilitate communication, harmonize actions, and build consensus because of their unique boundary properties.

However, the existing literature on boundary objects reveals a critical gap. Much of the research falls into a functionalist trap, celebrating the bridging role of these objects without systematically interrogating the underlying mechanisms that enable this function. The "how" behind their success often remains a black box. Furthermore, there is an undertheorized tendency to view boundary objects as inherently positive tools, with insufficient attention paid to their potential dual effects. Their capacity to act not only as a collaborative glue but also as a "blindfold"—masking deeper conflicts, reinforcing power imbalances, or leading to goal alienation—is rarely assessed systematically. This oversight limits both our theoretical understanding and our ability to design and implement these tools effectively in complex, high-stakes governance arenas.

To address these gaps, this paper aims to answer the following core research questions: a). What are the key functions of boundary objects at the science-policy interface, and through what underlying mechanisms do they operate? b)What are the dual effects of boundary objects, acting as both a cohesive "glue" and a potentially restrictive "blindfold" in environmental governance contexts? c)How do typical boundary objects in China's ecological governance (e.g., policy frameworks and ecological indicators) function in practice, and what does their application reveal about designing more effective and resilient governance tools?

By answering these questions through a comparative analysis of key Chinese cases, this study makes three primary contributions. First, it develops an integrated function-mechanism-effect framework to move beyond description toward causal explanation. Second, it systematically theorizes the dual nature of boundary objects. Third, it provides empirical insights from China's unique state-led governance system, offering a more in-depth theoretical understanding of boundary objects and practical guidance for their effective use in complex environmental governance.

2 Theoretical foundations of boundary objects

The concept of boundary objects originates from the study of scientific practices and social interactions, and at its core addresses the question of how different social groups (e.g., scientists, policymakers, community representatives) can work together effectively in the absence of complete consensus. Its theoretical power stems from several core tenets:

1. Heterogeneity. The theory recognizes and respects that different groups have their own unique knowledge systems, language habits, and interests, and does not require that one group adopt the perspective of the other (Carlile, 2004). This is what distinguishes it from integration models that pursue uniform language or complete consensus.
2. Interpretive Flexibility: This is the most central feature of boundary objects. The same object (e.g., a map of ecosystem services) may represent complex spatial data and ecological models for scientists; for policymakers, it may be the basis for delineating protected areas or designing ecological compensation; and for local communities, it may be about livelihoods and cultural identity. Each party can understand and use it from its own perspective without having to fully understand the complex logic of the others (Carlile, 2004).
3. Concrete Abstraction: Boundary objects are both concrete (e.g., a report, a piece of software), capable of being manipulated and discussed jointly, and abstract, capable of carrying the meanings and goals of different groups. This combination of concrete and abstract makes them it a focal point that can anchor collaboration (Chong et al., 2017).
4. Process Orientation: The value of a boundary object is not embedded in its material form, but in the process of social interaction it catalyzes. It is a verb rather than a noun, and its vitality is embodied in the negotiation, debate, co-revision, and ongoing interactions around it (Wiegleb and Bruns, 2023). Thus, a boundary object should be assessed not only by itself, but also by the social processes in which it is embedded and shaped.

Crucially, a generic governance tool becomes aboundary object not because of its inherent form, but when it is actively used to mediate collaboration across different social worlds (e.g., science, policy, and public). Its defining attribute is this functional role in bridging heterogeneous groups, which distinguishes it from conventional policy instruments that may operate within a single community.

In the practice of the science-policy interface (SPI), this theory provides a powerful analytical framework for understanding why certain tools and platforms are successful in facilitating cross-boundary collaboration. It reminds us that effective SPI tool design should not aim to create a perfect product that everyone agrees with 100%, but rather to create a product that brings different actors to the same table and allows them to work together productively.

3 Multidimensional functions of boundary objects

The concept of boundary objects was first introduced by Star and Griesemer (1989) to describe items possessing both interpretive flexibility and structural robustness. In the context of the science-policy interface, they are best understood as shared points of reference (e.g., maps, models, or even concepts) that enable diverse social groups, such as scientists and policymakers, to

collaborate effectively around a common task without necessarily reaching a full consensus on its meaning. Boundary objects do not play a single role in the science-policy interface, but perform at least three interrelated core functions, depending on the needs of the context.

3.1 Bridging the cognitive divide

This constitutes the most fundamental function of the boundary object. Science and policy represent two distinct realms of cognitive engagement. Boundary objects can markedly reduce the transaction costs of cross-boundary communication by establishing a shared reference point. Scenarios, a common boundary object, do not aim to accurately predict the future. Instead, they provide a shared language and imaginative space for scientists and policymakers to discuss long-term strategies by constructing several possible future scenarios (Pradhan et al., 2024). Similarly, effective visual maps or data dashboards have been shown to break down disciplinary barriers by transforming complex scientific data into information that policymakers can understand and use (Pirrone et al., 2022). In this process, the function of boundary objects is not to convey full scientific details, but to translate and encode information into a shared medium, thereby creating a cognitively mediated zone that is sufficient to support effective dialog.

3.2 Facilitating collaboration in practice

Beyond communication, boundary objects assume the role of platforms that facilitate the organization and coordination of tangible actions. In the context of transnational environmental governance, a widely accepted monitoring protocol or assessment framework (e.g., the assessment reports of IPBES) functions as a significant boundary object (Borie et al., 2021). Such an initiative serves to standardize the methodologies employed for data collection and analysis, while also facilitating the collaborative efforts of scientists and officials from diverse international institutions and organizations within a unified workflow framework. To complete this report, there must be continuous coordination, division of labor, and cooperation among all parties. In this case, the boundary object functions as a magnet, attracting and organizing dispersed actors to collaborate on a common task (Wiegleb and Bruns, 2023). This collaborative process itself has the potential to deepen mutual understanding and trust, thereby laying the foundation for more profound cooperation.

3.3 Giving legitimacy to the political process

In contentious and controversial policy domains, boundary objects fulfill a political role, including the stabilization of expectations, the building of consensus, and the legitimization of decisions. Decisions that are informed by a boundary object—such as a comprehensive ecological and socio-economic assessment report—that incorporates contributions from multiple stakeholders (scientific community, government, NGOs, and local communities)—are characterized by enhanced transparency, credibility, and acceptability (Wiegleb and Bruns, 2023). In this context, the boundary object functions as a medium for implementing procedural justice. This approach demonstrates to the external community that the decision-making process is open, inclusive, and founded on scientific evidence and a range of claims. The participatory nature of the process can enhance stakeholder acceptance of the final outcome, thereby reducing resistance to policy implementation (Dunn et al., 2017).

4 Core mechanisms of boundary objects

These three core mechanisms form the engine of a boundary object, explaining how it performs its functions. They are not independent but work in concert, creating a causal pathway from function to effect. Three core mechanisms are behind the ability of boundary objects to achieve the multidimensional functions described above.

4.1 Interpretive flexibility

As previously stated, this is intrinsic to the capacity of boundary objects to cross boundaries. This approach enables participants from diverse backgrounds to attribute distinct meanings to the same object, thereby fostering cooperative relationships without the need to eliminate differences. A paradigmatic example is the concept of ecosystem services or nature's contributions to people. From the perspective of ecologists, it serves as a scientific framework for analyzing ecosystem functioning. From the perspective of economists, it provides a pathway for valuation. From the perspective of policymakers, it is a policy tool for promoting ecological compensation and green development. And finally, from the perspective of the general public, it is the lingua franca for understanding nature's benefits (Balvanera et al., 2020). This flexibility enables all parties to identify their respective interests and align accordingly, fostering the establishment of broad coalitions.

4.2 Materialization and structuring

A considerable number of boundary objects function by materializing abstract knowledge or imprecise objectives, thereby rendering them tangible, actionable, and open to discussion. To illustrate, a computer model of climate change adaptation encapsulates a multitude of complex variables and algorithms within a user interface. This interface enables policymakers to simulate the consequences of various policy options by adjusting the model's parameters, thereby circumventing the necessity of comprehending its intricate inner workings (Chong et al., 2017). This visualization process has been demonstrated to effectively lower the threshold for non-specialists to utilize scientific instruments. Concurrently, boundary objects function as guides for interactions by means of structuring. A structured agenda, a standardized form, and a set of evaluation indicators invisibly delineate the boundaries of the discussion, the priority of the issues, and the manner of presenting the information. Consequently, these elements render the originally diffuse discussion more focused and efficient.

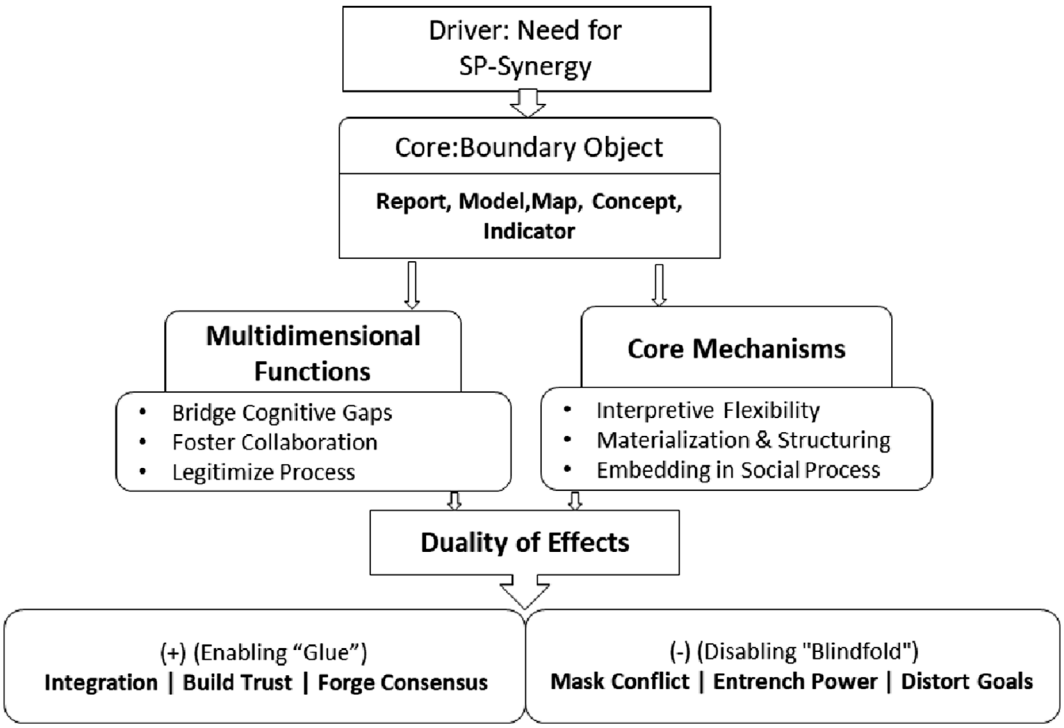

FIGURE 1
Boundary object action mechanism model.

4.3 Embedding in social processes

A boundary object, by definition, cannot exist in isolation; it must be embedded in a continuous process of social interaction in order to come to life. A meticulously crafted report cannot be considered a true boundary object if it remains merely a static entity on a shelf. Its utilization is imperative in authentic social scenarios, including seminars, policy hearings, and multi-party dialog platforms (Lewis et al., 2023). In such scenarios, discussions, debates, and even arguments surrounding the boundary object are pivotal to its functionality. It is through these social processes that misunderstandings between different groups are clarified, hidden assumptions are exposed, and new consensus gradually emerges from the interaction. Consequently, effective boundary practices are frequently associated with meticulously designed participatory processes and institutional frameworks that ensure the effective activation of boundary objects (Norström et al., 2020).

To visualize the relationship between these concepts, this study proposes the "Boundary Object Mechanism Model" (Figure 1). This model integrates our function-mechanism-effect framework. It illustrates the core causal logic we propose: specific mechanisms (the engine, e.g., interpretive flexibility, visualization) are activated to perform certain functions (the action, e.g., bridging cognition, facilitating collaboration). These functions, in turn, produce dual effects-acting as either a cohesive glue or a restrictive blindfold—depending on the specific contextual conditions in which the boundary object is deployed. This model is not a static representation but a conceptual tool for analyzing the dynamic life cycle of a boundary object.

This theoretical framework provides a powerful lens for examining real-world governance practices. The following sections will now operationalize this model by applying it to a series of high-profile boundary objects from China's ambitious ecological governance agenda. This case-based analysis serves a dual purpose: first, to test and demonstrate the analytical utility of our framework in a concrete setting, and second, to generate nuanced, context-specific insights into how boundary objects operate within a complex, state-led governance system. By systematically dissecting these cases through the function-mechanism-effect logic, we can move beyond abstract theory to understand their practical application and implications.

5 Methodology and case selection

This study employs a qualitative, theory-testing approach, combining a conceptual framework with multiple case studies to ensure rigor and transparency.

5.1 Data sources and analytical method

Data are drawn from a systematic review of publicly available documents, including a) official policy documents and government reports(e.g., national-level Five-Year Plans, ministerial circulars on ecological redlines, and white papers on climate policy), b) peer-

TABLE 1 Comparative analysis of typical boundary objects in China's ecological governance.

Characteristic dimension	Ecological protection red line (bottom line constraint)	Mountain, river, forest, farmland, lake, grassland, and desert ecosystems (system integration)	"The two mountains theory" (value leadership)	"Dual carbon goal" (goal driven)	Ecological indicators (e.g., GEP, ESV)
Core essence	Spatialized, legally binding ecological security floor (Gao, 2014)	Holistic, systemic philosophical and narrative framework for ecological governance (Chen et al., 2025)	Political economy assertions linking ecological conservation and economic development (Zhao and Yang, 2015)	Clear, quantitative, time-bound national transformation goals (Hu, 2021; Zhang, 2021)	Quantitative, tools for assessing ecosystem status, function or value (Wang et al., 2021; Song and Ouyang, 2023)
Key Functions (in SPI)	Bridging the cognitive gap (clarity of boundaries); legitimizing the process (legal basis)	Bridging the cognitive divide (common language); facilitating practice collaboration (cross-sectoral integration)	Bridging the Cognitive Divide (New Values); Legitimizing the Process (Political Leadership)	Bridging the Cognitive Divide (Clear Direction); Facilitating Practice Collaboration (System Transformation)	Bridging the cognitive divide (simplifying complexity); promoting practice collaboration (common assessment basis); giving legitimacy to the process (basis for decision-making)
Core mechanisms of action	Visualization (maps); structuring (control rules); embedding in social processes (planning)	Flexibility of interpretation (multiple interpretations); embedded in social processes (major projects)	Flexibility of interpretation (multiple paths); embedded in social processes (appraisal, incentives)	Figurative (numerical goals); Structured (timetables); Embedded in social processes (national strategies)	Visualization (numerical values); Structuring (accounting framework); Flexibility of interpretation (multiple applications); Embedding in social processes (policy evaluation)
Adhesive effects	Forcing protection of key ecological space; curbing disorderly development	Promote integrated ecosystem-based management; break down sectoral fragmentation	Generate new green businesses; reshape the concept of development	Strongly promote energy and industrial transformation; catalyze green technology and investment	Make ecological value visible; support ecological compensation and performance assessment; guide green decision-making
Risks or blindfolds	Rigid delimitation may ignore local needs and knowledge; entrenching expert power	Conceptual abstraction may lead to alienation of objectives; masks sectoral conflicts of interest	Possible "selective" use; decoupling between rhetoric and practice; entrenching certain development models	"One-size-fits-all; "campaign carbon-reduction"; masking regional/sectoral imbalances	Over-simplification of complex systems; alienation of "digital governance"; may be used to "greenwash" or mask real problems
Main actors/targets	Planners, policymakers, scientists, enterprises	Multi-government departments, scientists, project implementers	Local officials, entrepreneurs, public	Central and local governments, various industry sectors, enterprises, research organizations	Policymakers, scientists, evaluation organizations, financial institutions, public
Level of abstraction/ concreteness	Highly concrete (spatial red lines)	Highly abstract (philosophical concepts)	Abstract (value assertions) but with concrete practices	Concrete (numerical targets) but with broad abstract implications	Concrete (numerical values/indexes) but representing complex ecological processes and values

reviewed academic literature retrieved from major databases like Web of Science and CNKI using keywords such as "Ecological Protection Red Line," "Two Mountains Theory," and GEP, and c) authoritative media analysis from sources like People's Daily and Xinhua News Agency to trace the evolution of policy discourse. The analysis uses a structured qualitative content analysis guided by the function-mechanism-effect framework. This process involved a two-stage coding procedure. In the first stage, text segments from the collected data were coded deductively according to the predefined categories of framework. In the second stage, inductive coding was employed to identify emergent themes and patterns within each case, particularly concerning the interactions between different boundary objects. This structured approach ensures that the analysis is not merely descriptive but explicitly tests the causal logic proposed by the framework. Each case was coded for its core functions, mechanisms, and dual glue and blindfold effects, with the results synthesized in the comparative analysis presented in Table 1.

5.2 Rationale for case selection

To ensure methodological rigor, the five cases—the Ecological Protection Red Line, the "mountains, waters, forests, lakes, grasses,

and sands" system, the "Two Mountains Theory," the "Dual Carbon Goal," and ecological indicators (e.g., GEP)—were purposively selected based on a preliminary review of national policy documents to identify the most prominent and frequently cited governance initiatives that constitute a representative matrix of China's contemporary ecological governance. The selection criteria ensured diversity across key dimensions: a) governance logic (from hard constraints to soft value guidance), b) form and abstraction (from concrete tools to abstract concepts), and c) scale of influence. Furthermore, all chosen cases are d) high-profile national initiatives with sufficiently rich public data to allow for a well-grounded analysis. By examining this matrix, the study aims to generate deeper insights into the complex reality of using boundary objects in a large-scale governance context.

6 Case perspective: a matrix of boundary objects in China's ecological governance

The theoretical framework previously outlined offers a universal perspective on the understanding of boundary objects. This chapter employs an exploratory approach by directing its attention to China, a nation that is currently engaged in one of the world's most ambitious and exploratory ecological governance practices. The objective of this endeavor is to test and deepen the aforementioned framework by examining China's unique ecological governance practices. Based on the rationale explained in the methodology section, a selection of four macro-boundary objects that are iconic in China's ecological civilization development will be analyzed, and an exploration of how specific ecological indicators function as more nuanced boundary objects will be conducted. Collectively, these cases demonstrate the establishment of a matrix of governance tools with complementary functions (see Table 1).

The subsequent section will provide a detailed exposition of the various types of boundary objects in Table 1.

6.1 Bottom-line constrained boundary object

The "ecological protection red line" is a typical bottom-line constrained boundary object. It transforms the bottom line requirements of national ecological security into a spatially precise and legally effective "red line" map through the mechanism of visualization and structuring (Gao, 2014). The line itself constitutes a powerful boundary object, thereby providing a common reference for scientists (to establish a basis for delineation), planners (for spatial control), decision makers (to approve projects), and enterprises (to assess investment risks) (Li, 2014; Jiang et al., 2015; Zheng and Ouyang, 2014). This object greatly bridges the cognitive divide. It is embedded in the statutory process of territorial spatial planning, embodying a mechanism embedded in social processes. Specifically, the red line is formally integrated into China's national, provincial, and municipal spatial plans under the framework of laws like the Land Management Law and related spatial planning regulations. This means that any development plan or construction project that conflicts with the red line is legally prohibited from approval, thus legitimacy to the most stringent protection policies (Zhang et al., 2019). The adhesive effect of this policy is that it prioritizes ecological protection over economic and social development, effectively curbing the encroachment of critical ecological space. However, the risk of blinders also exists. Rigid top-down delineation may solidify power by overreliance on scientific judgment by technical experts, ignoring the livelihood needs and local knowledge of local communities and risking obscuring deeper socio-economic conflicts (Wiegleb and Bruns, 2018).

6.2 System-integrated boundary object

The concept of "mountains, waters, forests, lakes, grasses, and sands" serves as a paradigmatic example of a system-integrated boundary object. The text demonstrates a marked reliance on interpretive flexibility, offering a comprehensive narrative framework that is replete with Chinese philosophical wisdom and holistic thinking. The concept under discussion functions as a unifying framework that facilitates communication and collaboration among scientists and managers from disparate departments, including water conservancy, forestry, environmental protection, and natural resources. By adopting a unified language and conceptual framework under the rubric of "community of life," this initiative aims to transcend the existing disciplinary and organizational boundaries, thereby fostering a more integrated and collaborative approach to research and management issues (Chen et al., 2025; ZOU et al., 2018; Zheng and Zhuang, 2020). It is embedded in social processes through a series of major ecological restoration projects as a vehicle, forcing cross-sectoral collaboration of practices. The phenomenon of glue governance has been demonstrated to facilitate integrated ecosystem-based governance, thereby resolving the long-standing challenge of multiple stakeholders exerting influence within a given ecosystem. However, the risk is that, as a highly abstract concept, it may lead to the alienation of objectives due to excessive flexibility in interpretation. In the absence of a specific coordination mechanism and assessment criteria, it can be reduced to a slogan to cover up sectoral conflicts of interest. For instance, in translating this holistic concept into practice, some large-scale restoration projects have adopted simplified approaches, such as widespread planting of a single tree species in arid regions. While fulfilling the mandate of a major project, this practice ignores local ecological conditions and biodiversity needs, leading to low survival rates and unintended negative ecological consequences, a clear example of goal distortion driven by a simplified interpretation of a complex concept (Shi et al., 2022; Shi et al., 2025).

6.3 Value-led boundary object

The "Two Mountains Theory" is an archetypal value-led boundary object. By means of a political economy assertion with considerable appeal and interpretive flexibility, it is committed to reshaping the dichotomy between protection and development. Furthermore, it provides fundamental political and moral legitimacy to green development (Hu et al., 2019). It establishes a

novel shared value system, facilitating discourse among local officials, entrepreneurs, and the public. This initiative significantly reduces the value perception gap (Qin et al., 2018; Hu and Zhang, 2018). It is embedded in the social (political) process, as evidenced by the introduction of GEP (gross ecosystem product) accounting in the cadre appraisal system. This guides the direction of local governments' practical collaboration (Hao et al., 2022). The phenomenon of the "glue effect" signifies the profound liberating of ideas, which has subsequently given rise to novel business ventures such as eco-tourism and eco-agriculture. However, there is a concern that this approach may be utilized selectively, thereby serving to reinforce existing power structures. In some cases, this discourse may be perceived as decoupling between rhetoric and practice, a term used to describe the misrepresentation of environmental sustainability efforts. For instance, a local government might use the "Two Mountains Theory" to justify developing a high-end tourist resort around a pristine lake, branding it as eco-tourism. However, this selective use might ignore the massive water and energy consumption of the resort and the pollution from increased traffic, thereby achieving decoupling between rhetoric and practice while creating new ecological pressures. This phenomenon can be likened to a blindfold, serving to obscure the discrepancies between the purported development model and its actual consequences. This is precisely the "blindfold" that obscures the real conflict of development models.

6.4 Goal-driven boundary object

The "Double Carbon Targets" is a typical goal-driven boundary object. It is a typical goal-driven boundary object, which, through visualization and structuring (clear year and quantitative targets), sets an indisputable hard constraint on the economic and social systematic transformation of the whole country. It provides a common focus for all actors and strongly bridges the cognitive gap about the direction of transformation (Ouyang et al., 2021; Liu et al., 2021). The phenomenon of glue is indicative of the facilitation of unparalleled cross-sectoral collaboration on practices in energy, industry, transportation, and other domains. This has given rise to a substantial market for green technology innovation and investment. However, there is a risk that this approach may result in a "one-size-fits-all" in policy implementation, which is a common form of target alienation. Furthermore, the strategic allocation of reduction pathways and the distribution of responsibility may also serve to obscure profound conflicts, such as the persistent disparities in development between regions and industries, thereby transforming into a novel form of blindness.

6.5 Indicator boundary objects

As indicated by the aforementioned macro framework, a multitude of boundary objects, manifesting as indicators, have come to the fore within China's ecological governance praxis. For instance, the application of GEP (Gross Ecosystem Product) accounting and ESV (Ecosystem Service Value) assessment is being actively explored (Ouyang et al., 2013; Liu et al., 2020). By visualizing complex ecological processes and ecosystem functions into quantifiable and comparable values, these indicators provide decision makers with a basis for measuring the effectiveness of ecological protection, ecological compensation, and spatial planning optimization. The fundamental rationale for the transformation of these indicators into boundary objects is rooted in their flexibility of interpretation and concrete abstraction. From the perspective of ecologists, they serve as a means of evaluating ecosystem health and functionality. From the perspective of economists, they facilitate the incorporation of ecological values into economic decision-making processes. From the perspective of policymakers, they function as a reference point for evaluating performance and formulating policies. This multiplicity of interpretations enables actors from diverse fields to engage in dialogue and negotiation concerning these indicators. As McCool and Stankey (2004) have indicated, the efficacy of eco-indicators may be contingent upon a certain degree of ambiguity and negotiability, as opposed to absolute precision. This attribute engenders an opportunity for the establishment of a consensus among disparate stakeholders. This approach fosters an environment conducive to the establishment of connections among diverse stakeholders. However, it is imperative to acknowledge the potential risks associated with indicator-based boundary objects. In the event of inadequate design or the absence of transparent integration into social processes (Norström et al., 2020), these systems risk oversimplifying complex eco-social systems, potentially resulting in the alienation of digital governance (Berrouet, Machado and Villegas-Palacio, 2018) or its utilization as a medium for digital governance. As posited by Berrouet, Machado, and Villegas-Palacio (2018), this phenomenon may even be employed as a euphemism for green performance, thereby obfuscating authentic ecological concerns. Consequently, the deliberate design and implementation of these boundary objects are paramount.

6.6 The matrix in action: synergies and tensions among boundary objects

As Table 1 illustrates, these boundary objects display distinct characteristics. However, their true power in China's ecological governance lies not in their isolated application, but in their dynamic interaction as a coherent, albeit complex, governance tool matrix. This matrix is more than a simple collection; it is a functioning system where the tools synergistically enable and reinforce one another, creating a transformative governance logic.

This synergy operates through a clear causal chain. For example, the highly abstract "Two Mountains Theory" (value leadership) provides the political legitimacy and overarching vision. This vision is then made tangible and operational through ecological indicators like GEP, which translates ecological assets into a measurable metric for performance appraisal. This, in turn, drives green development practices which must occur within the non-negotiable spatial boundaries set by the "Ecological Protection Red Line" (bottom-line constraint). In this chain, the GEP without the "Two Mountains Theory" is just a number; the Red Line without a development model to guide what happens outside it is just a fence. It is their interaction that creates a powerful, multi-layered governance system.

Furthermore, the "Dual Carbon Goal" (goal-driven) acts as an overarching forcing mechanism, compelling the entire matrix to align with a low-carbon trajectory. It forces the holistic philosophy of "mountains, waters. . ." (system integration) to be interpreted not just for general restoration, but for restoration that enhances carbon sinks. This demonstrates how a hard, quantitative target can discipline the interpretation of softer, more abstract boundary objects.

However, this matrix is also fraught with tensions. The top-down, rigid nature of the Red Line can clash with the flexible, locally-adapted development encouraged by the "Two Mountains Theory," creating policy conflicts on the ground. Similarly, the rush to meet "Dual Carbon" targets can lead to reductions that contradict the systemic, long-term thinking promoted by the "mountains, waters. . ." philosophy. Understanding these synergies and tensions is critical for managing the matrix effectively.

7 Conclusion and outlook

This paper systematically dissects the boundary object in the science-policy interfaceby developing and applying a "function-mechanism-effect" analytical framework to the rich practice of ecological governance in China. Our analysis reveals that boundary objects are not static tools, but dynamic instruments that connect science and policy through the functions of bridging cognition, facilitating collaboration, and legitimizing decisions. These functions are powered by the core mechanisms of interpretive flexibility, structuring, and social embedding.

Crucially, our study demonstrates that the effects of these objects are dual-sided. While they can act as a glue to foster integration, they also carry the risk of becoming blindfolds that obscure conflict, entrench power, and lead to goal alienation. The case study of China vividly confirms and deepens this theoretical framework. It shows how different types of boundary objects constitute a complementary matrix of governance tools that systematically advance ambitious policy agendas. Their power lies in their synergistic interaction, but this is accompanied by inherent tensions and risks that require careful management.

Theoretically, this study makes two key contributions. First, by proposing the function-mechanism-effect framework and the governance matrix concept, it provides a more dynamic and systemic approach to analyzing boundary objects. Second, it expands boundary object theory by conceptualizing how abstract political discourses like the "Two Mountains Theory" function as powerful boundary objects. Unlike classic material objects, their robustness stems not from shared material properties but from a shared, top-down political context. This finding extends the theory's applicability from science-centric problems to complex, politically-driven governance arenas.

Our central finding is that the effectiveness of boundary objects is a matter of process design and political ecology, not just technical design. The fate of a boundary object depends profoundly on the power structures, institutional environment, and socio-cultural context in which it is embedded.

Based on this, we propose three forward-looking principles for practice:

1. From static tool design to dynamic portfolio management: Focus on the interactions within the governance matrix. This involves establishing feedback loops where the effects of one tool (e.g., GEP) are used to refine another (e.g., Redline boundaries).
2. From product consensus to process fairness: The legitimacy of a boundary object like GEP comes not from the final number, but from a transparent and participatory process that incorporates diverse stakeholder values.
3. From generic tools to context-aware assessment: Before deploying a new boundary object, policymakers should use a context checklist to proactively identify potential power imbalances, stakeholder conflicts, and mechanisms for revision.

Ultimately, studying boundary objects is a means to an end: reflecting on how to build more inclusive, adaptive, and resilient governance in an increasingly complex world.

Author contributions

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Conflict of interest

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