

Article

Knowledge Intermediaries in State-Led Environmental Governance: Institutional Access, Social Embeddedness, and Uneven Outcomes in China's Erhai Lake Basin

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Abstract

In China's Erhai Lake basin, strict agricultural pollution control policies have reduced ecological degradation but severely disrupted smallholder livelihoods, creating an urgent need for institutional actors capable of mediating between state mandates and rural communities. This study examines Science and Technology Backyards (STBs), university-based knowledge intermediaries, as a distinctive governance mechanism embedded within China's state-led environmental governance system. Drawing on 60 days of ethnographic fieldwork and 33 semi-structured interviews with 36 participants in Gusheng Village, Dali City, we develop a socio-technical institutional framework that conceptualizes STB effectiveness as depending on the joint operation of three dimensions: technological rationality, social embeddedness, and institutional access. Empirically, the findings show that STBs operate through three bridging mechanisms: technical correction, power adjustment, and market linkage. However, their influence is structurally uneven. Vertically, STB engagement is strong at the prefectural level but weakens sharply at township and village levels. Horizontally, technology diffusion concentrates in core villages and disproportionately benefits large-scale farmers over smallholders. Market linkage remains the weakest mechanism due to deep institutional deficits in cooperative development, supply chain infrastructure, and state–market coordination. These findings contribute to understanding how knowledge intermediaries produce uneven governance outcomes within hierarchical political systems.

Keywords: knowledge intermediaries; socio-technical institutions; institutional access; state-led environmental governance; smallholder inclusion; rural China



Academic Editor: Jianming Cai

Received: 3 July 2026

Revised: 24 July 2026

Accepted: 30 July 2026

Published: 1 August 2026

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1. Introduction

China's pursuit of ecological civilization has generated a fundamental governance tension: stringent environmental regulations reduce pollution but frequently disrupt the livelihoods of smallholder farming communities that depend on the very practices being restricted [1,2]. This tension is particularly acute in lake basin governance, where agricultural non-point source pollution control requires rapid, comprehensive changes to farming systems that have sustained rural households for generations [3,4]. Finding institutional mechanisms capable of mediating between state environmental mandates and

local livelihood realities represents one of the most pressing challenges in China's rural governance [5].

The Erhai Lake basin in Yunnan Province exemplifies this challenge. For decades, local livelihoods depended on Erhai Lake fisheries, Cangshan Mountain forestry, and intensive farmland cultivation in the dam area. Repeated cyanobacterial blooms and progressive ecological degradation prompted escalating governance responses. Since 2017, policies including garlic cultivation bans, chemical fertilizer restrictions, and large-scale land transfers have significantly reduced agricultural pollution but have simultaneously dismantled traditional Bai ethnic farming livelihoods. Fishermen lost income sources, garlic farmers experienced sharp earnings declines, and several villages initiated collective petitions over land transfer payments and changes to drinking water sources. This governance context created structural demand for intermediary actors capable of translating rigid state policies into locally adaptive practices [2].

In response, the Science and Technology Backyard (STB) model was introduced into Erhai governance. STBs are university-based knowledge intermediaries that integrate scientific research, technology extension, and community engagement within a single organizational platform [6,7]. In 2021, a team led by Academician Zhang Fusuo established an STB presence in Gusheng Village, oriented toward non-point source pollution control and green agricultural transformation. This study examines how the STB operates within this governance context, what mechanisms it employs, and why its effectiveness is structurally uneven across governance levels, village types, and farmer groups. Specifically, this paper asks: under what structural conditions does a socio-technical institution produce integrated versus uneven governance outcomes in a state-led environmental governance system? To address this question, we draw on 60 days of ethnographic fieldwork and 33 semi-structured interviews with 36 participants conducted in Gusheng Village and five surrounding natural villages between June and August 2025.

1.1. Theoretical Perspective: Adaptive Governance, Social Embeddedness, and Institutional Access

Understanding the role and operational logic of the STB in Erhai Lake governance requires theoretical frameworks that can account for three analytically distinct but empirically interrelated dimensions: the governance structures within which it operates, the social relationships through which it functions, and the institutional access mechanisms through which it acquires legitimacy and influence. This study draws on adaptive governance theory and social embeddedness theory as complementary starting points, and extends them by introducing institutional access as a third analytical dimension necessary for understanding knowledge intermediaries in strongly state-led governance contexts.

Adaptive governance emphasizes that complex socio-ecological challenges cannot be addressed through top-down management by a single entity; instead, effective governance requires multi-stakeholder collaboration, continuous learning, and institutional flexibility [8,9]. The framework highlights the importance of cross-level learning mechanisms, governance resilience under uncertainty, and bridging organizations that connect state actors, research institutions, communities, and markets [10,11]. These dimensions are directly relevant to understanding STBs as multi-level collaborative platforms. However, adaptive governance theory was developed primarily in Western pluralist contexts and has two limitations for the present study. First, it assumes relatively open institutional environments in which non-state actors can participate as autonomous agents, an assumption that does not hold in China's Party-state governance architecture, where access to policy processes requires active institutional positioning rather than open invitation. Second, it focuses on how governance systems adapt over time but offers limited guidance on how an intermediary organization initially acquires the access and legitimacy necessary to

participate in governance at all. These limitations reflect a broader critique that adaptive governance practices are profoundly shaped by existing power structures, administrative hierarchies, and the distribution of institutional resources [12,13].

Social embeddedness theory addresses the relational dimension that adaptive governance underspecifies. Granovetter's foundational argument [14] establishes that economic action is shaped by social relationship networks and that institutional effectiveness depends on actors' ability to integrate into local trust structures and cultural norms. In China's rural contexts, only external actors embedded in local social networks can establish the stable cooperative relationships necessary for sustained intervention, and a mutually reinforcing dynamic between economic exchange and social relations underpins this embeddedness [15]. Sang and Li's concept of differential embeddedness [16] refines this further, showing that STBs undergo a staged identity transformation from outsider guests to trusted partners, and that this transformation follows differentiated trajectories across different community types. This relational framework is essential for explaining why the STB produces different governance outcomes across villages with similar policy environments. However, social embeddedness theory focuses primarily on horizontal relationships between an organization and its community and does not theorize how vertical relationships with state actors are constructed and maintained, a dimension critical to understanding how STBs function within China's administrative hierarchy [17].

Building on both frameworks and addressing their shared limitation, this study introduces institutional access as a third analytical dimension. In China's governance context, the STB's ability to function as a knowledge intermediary depends not only on scientific credibility or community trust but on its active integration into the political and administrative structures of the Party-state. This includes mechanisms such as the academician-party secretary direct dialogue that grants privileged policy access, participation in Party-building activities at the village level that generates political legitimacy at the grassroots, and strategic positioning within the project-based governance logic of township and county governments [17,18]. These mechanisms have no direct equivalent in Western adaptive governance or social embeddedness frameworks and are not theorized within existing knowledge-intermediary or boundary organization literature [19,20]. In China, universities and research institutions occupy a distinctive semi-institutional position as knowledge intermediaries, holding sufficient state legitimacy to access policy processes, sufficient technical credibility to engage farming communities, and sufficient organizational flexibility to operate across governance levels [6,21], but the conditions under which this position translates into effective governance influence have not been systematically examined.

This study therefore proposes a socio-technical institutional framework that conceptualizes STB effectiveness as depending on the joint, rather than separate, operation of three mutually reinforcing dimensions: technological rationality, through which the STB generates scientific authority via monitoring, experimentation, and evidence production; social embeddedness, through which it builds trust, cultural legitimacy, and relational credibility within rural communities; and institutional access, through which it acquires and maintains a position within China's governance hierarchy that allows scientific knowledge to be translated into policy-relevant authority. The framework's core argument is that the absence or weakness of any single dimension undermines the effectiveness of the other two: technological outputs without social embedding lack community legitimacy; social relations without institutional access lack policy durability; and institutional positioning without technological credibility lacks authority. This interdependence, and the conditions under which it produces uneven rather than integrated governance outcomes, is the central analytical question the paper pursues empirically in Sections 4–6.

1.2. Research Methods and Case Selection

This study employs a single-case ethnographic design, with the Gusheng Village area in Wanqiao Town, Dali City serving as the research site (see Figure 1). Single-case ethnographic designs are appropriate when the research aim is to generate an in-depth, mechanism-oriented account of how a specific institutional form operates within a specific governance context, rather than to test hypotheses across cases [22,23]. The Gusheng Village area was selected for three reasons. First, it encompasses six natural villages—Gusheng, Nanzhuang, Zhongzhuang, Beizhuang, Yangxi, and Beiyangxi—constituting the core implementation zone for Erhai Lake governance policies, making it the most policy-intensive site in the basin. Second, it was the earliest and most sustained site of STB engagement in the basin, allowing examination of a relatively mature intermediary-governance relationship rather than an emergent one. Third, the presence of six villages with distinct governance trajectories within a single administrative area allows comparison of differentiated STB engagement patterns under common policy conditions, providing internal variation without requiring a multi-case design. The findings are presented as context-specific propositions rather than generalizable claims.

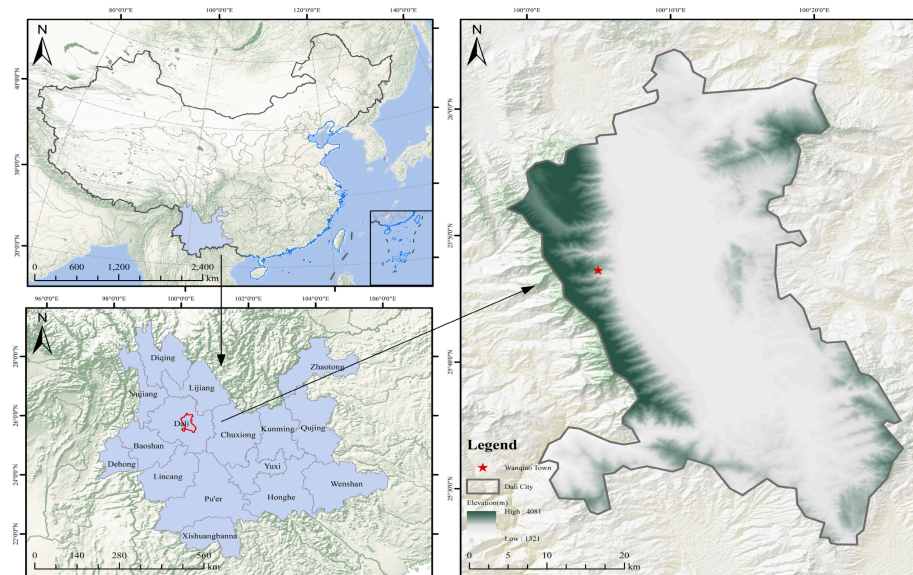


Figure 1. Study area location: Wanqiao Town, Dali City, Yunnan Province, China. Cartographic elements including scale bar, north arrow, and coordinate reference system (WGS 1984) are included. Base map data sourced from the National Catalogue Service for Geographic Information (tianditu.gov.cn); Map drawn by authors.

Data were collected during a 60-day field investigation in the Gusheng Village area between 21 June and 20 August 2025. Two primary methods were employed: semi-structured interviews and participant observation. A total of 33 interviews were conducted with 36 participants across six categories: STB faculty and student researchers; government officials from Dali Prefecture and Dali City; village cadres from Wanqiao Town and two administrative villages; large-scale farmers; smallholder farmers; and enterprise and business representatives including homestay operators and agricultural supply store owners (see Table 1). The distribution of interviews across these categories is reported in Table 2. Smallholder farmers constitute the largest respondent group, ensuring that the study's findings on smallholder marginalization rest primarily on smallholders' own accounts rather than on institutional informants. Interviews focused on four thematic areas: the STB's daily operations and governance relationships; technology promotion processes and farmer responses; specific cases of conflict, mediation, and resolution during policy implementation;

and changes in household livelihoods since the introduction of Erhai governance policies. Each interview lasted approximately 50 to 100 min. With participants' consent, 30 of the 33 interviews were audio-recorded. For the remaining 3 interviews, where recording was not permitted, detailed field notes were taken immediately afterward. All 30 recordings were transcribed verbatim in Chinese within one week of each interview. Participant observation was conducted during field experiments, farmer training sessions, village public activities, and farmers' daily work, generating field notes that supplemented and triangulated the interview data.

Table 1. Overview of Data Collection and Analysis.

Component	Description
Study Site	Gusheng Village and five surrounding natural villages, Wanjiao Town, Dali City, Erhai Lake Basin
Fieldwork Period	21 June 2025 to 20 August 2025 (60 days)
Interview Method	Semi-structured interviews
Number of Interviews	33 interviews
Number of Participants	36 participants across 33 interviews (31 individual interviews and 2 group interviews)
Categories and numbers	Smallholders (20 interviewees); Large-scale farmers (4 interviewees); STB researchers (4 interviewees); Government officials (3 interviewees); Village cadres (3 interviewees); Enterprise/Cooperative representatives (2 interviewees)
Interview Duration	50 to 100 min per interview
Respondent Categories	Smallholder farmers, large-scale farmers, village cadres, STB researchers, government officials, enterprise and business representatives
Sampling Strategy	Purposive sampling for STB researchers, cadres, and officials; snowball sampling for farmers and enterprise respondents, with deliberate variation in landholding size, village location, and degree of STB engagement
Interview Language	Mandarin Chinese; Bai-language expressions in a small number of exchanges with elderly villagers, clarified in real time by the authors
Translation	Quotations translated into English by the authors and cross-checked against original transcripts
Recording and Transcription	Audio-recorded with participant consent in 30 interviews; 3 interviews documented through detailed field notes where recording was declined; all 30 recordings transcribed verbatim in Chinese.
Participant Observation	Field experiments, farmer training sessions, village meetings, daily interactions between STB members and villagers
Documentary Sources	Policy documents, project reports, local government materials, STB internal documents
Coding Procedure	Open coding → Axial coding → Mechanism identification
Validation Strategy	Triangulation across interviews, field notes, and documentary materials
Saturation	Interviews continued until no substantially new themes emerged
Positionality and Reflexivity	Authors affiliated with China Agricultural University, the STB's home institution; independent sampling chains, deliberate inclusion of critical respondents, and multi-source triangulation used to counterbalance institutional proximity
Ethical Measures	Institutional ethics waiver: oral informed consent obtained from all participants; anonymization of all quotations using coded identifiers (see Table 2)

Table 2. Interviewees Profile.

Interviewees Group	Code	Village(s)	Governance Level	Recruitment Strategy	No. of Participants	Interview Type	Analytical Purpose
Smallholders	SH01–SH20	All six natural villages	Village/grassroots	Purposive + snowball sampling	20	Semi-structured	Adoption of green technologies; perceptions of STB
Large-scale farmers	LF01–LF04	Nanzhuang, Zhongzhuang, Beizhuang	Village/grassroots	Introduced by STB researchers	4	Semi-structured	Technology adoption and market participation
STB researchers	STB01–STB04	Gusheng	Research actor (non-state)	Direct contact	4	Semi-structured	Knowledge transfer and institutional coordination
Government officials	GOV01–GOV03	Dali Prefecture, Dali City	Prefectural/municipal	Government departments	3	Semi-structured	Environmental governance and policy implementation
Village cadres	VC01–VC03	Wanqiao Town and two administrative villages	Township/village	Purposive + snowball sampling	3	Semi-structured	Grassroots implementation and STB engagement
Enterprise/Cooperative representatives	ENT01–ENT02	Gusheng	Market actor	Introduced by STB researchers	2	Semi-structured	Market participation

Note: Smallholder respondents were distributed across the six natural villages as follows: Gusheng (5), Nanzhuang (5), Zhongzhuang (4), Beizhuang (2), Yangxi (2), and Beiyangxi (2), corresponding to 5 respondents in the policy-driven transformation type, 11 in resource-endowment-based villages, and 4 in policy-constrained villages.

Respondents were identified through purposive sampling, beginning with STB faculty and student researchers who facilitated initial access to village cadres and local officials. Subsequent farmer and enterprise respondents were recruited through snowball sampling, with the authors deliberately seeking variation in landholding size, village location, and degree of STB engagement to avoid over-representing already-cooperative households. Interviews were conducted in Mandarin Chinese; a small number of exchanges with elderly villagers involved Bai-language expressions, which were clarified in real time by the authors. All quotations presented in the manuscript were translated into English by the authors and cross-checked against the original transcripts for accuracy.

Data analysis employed thematic analysis. Open coding of interview transcripts and field notes identified first-order concepts related to environmental governance, farmer livelihoods, technology extension, and policy implementation. Axial coding then grouped these concepts into second-order themes, which were aggregated through iterative comparison and discussion between the authors into three analytical mechanisms: technical correction, power adjustment, and market linkage (see Table 3). All interviews were transcribed verbatim in Chinese immediately after fieldwork. Local dialect expressions were standardized into Mandarin while preserving their original meanings. Coding was conducted by K.G., a native Chinese speaker, using the original Chinese transcripts to avoid semantic loss during translation. The coding framework and category boundaries were subsequently reviewed and discussed with all co-authors to improve analytical consistency. Triangulation across

interviews, participant observation notes, and documentary sources—including policy documents, project reports, local government materials, and STB internal records—was used to validate analytical claims. Interviews continued until no substantially new themes emerged, indicating analytical saturation.

Table 3. Coding Framework.

First-Order Concept	Second-Order Theme	Aggregate Mechanism
Pollution contribution misunderstanding	Epistemic correction	Technical Correction
Data-driven policy revision	Evidence-based governance	Technical Correction
Continuous nutrient monitoring practice	Evidence production	Technical Correction
Field experimentation and demonstration plots	Evidence production	Technical Correction
Fertilization scheme optimization	Technical adaptation	Technical Correction
Trust in expert knowledge	Expert legitimacy building	Power Adjustment
Policy resistance and farmer conflict	Conflict buffering	Power Adjustment
Cadre-researcher mediation	Bidirectional communication	Power Adjustment
“Every day-language policy translation”	Bidirectional communication	Power Adjustment
Long-term village residence and co-presence	Trust building	Power Adjustment
Differentiated training participation	Selective participation	Power Adjustment
Price instability and market uncertainty	Market vulnerability	Market Linkage
Ecological branding and certification	Market connection	Market Linkage
Weak cooperative organization	Institutional deficit	Market Linkage
Absent cold-chain and logistics	Institutional deficit	Market Linkage
Opportunity-cost rejection of new activities	Livelihood prioritization	Market Linkage
Large-farmer preference in enterprise matching	Diffusion bias	Market Linkage

With respect to positionality, the authors are affiliated with China Agricultural University, the institution that established and hosts the STB model nationally. While this institutional proximity facilitated access to STB researchers, internal documents, and policy networks, it may have shaped how the STB presented its work to the research team and introduced a risk of confirmation bias in data collection. The authors sought to counter-balance this through three strategies: recruiting smallholder farmers and village cadres through independent snowball chains rather than STB-mediated introductions; actively seeking out respondents who had limited or negative experiences with the STB; and triangulating STB accounts against farmer, cadre, and documentary sources. Limitations arising from this positionality are acknowledged in Section 7.

Ethical approval was not required under China Agricultural University’s institutional guidelines, which exempt non-interventional social science research involving voluntary adult participation and no collection of sensitive personal information. Prior to each interview, all participants were informed of the research purpose, the voluntary nature of

participation, and their right to withdraw at any time. Oral informed consent was obtained before each interview commenced. All quotations are anonymized using coded identifiers such as SH01, VC01, and STB01, as listed in Table 2. Potentially identifiable personal details were removed during transcription and analysis.

1.3. Paper Structure

The paper proceeds as follows: Section 2 reviews three bodies of literature directly relevant to the study: adaptive governance and the role of external organizations in rural governance; knowledge intermediaries in China's environmental governance; and existing research on Science and Technology Backyards, identifying the gaps this study addresses. Section 3 describes the Erhai Lake governance context across three historical phases and presents the typology of six natural villages derived from fieldwork. Section 4 analyzes the STB's three bridging mechanisms: technical correction, power adjustment, and market linkage, explaining how each was derived from the data and how the mechanisms interact. Section 5 examines the asymmetric embedding of the STB across vertical governance levels, horizontal village types, and internal farmer categories, including the strong top, weak middle, and weak grassroots pattern and the structural bias toward large-scale farmers. Section 6 develops the socio-technical institutional framework and situates the Erhai case within debates on adaptive governance in strongly state-led contexts. Section 7 presents the conclusions, policy implications specific to the Erhai governance context, study limitations, and directions for future research.

2. Literature Review

2.1. Adaptive Governance and the Role of External Organizations

Adaptive governance has emerged as a key framework for addressing complex socio-ecological challenges. Unlike top-down bureaucratic control, it emphasizes multi-stakeholder collaboration, continuous learning, and institutional flexibility [8,9]. A central insight from this literature is the importance of bridging organizations that connect different institutional levels and actors, facilitating knowledge transfer, resource allocation, and conflict resolution among governments, communities, and markets [10,11]. Farmer organizations similarly play a documented role in supporting smallholder integration into modern agricultural systems through technical assistance and resource coordination [24].

However, most adaptive governance scholarship draws on Western or pluralist governance contexts, where bridging organizations typically operate as independent entities with formal legal standing and autonomous decision-making capacity. In China, this institutional form is largely absent or constrained. Universities and research institutions instead occupy a distinctive semi-institutional position: they hold sufficient state legitimacy to access policy processes, sufficient technical credibility to engage farming communities, and sufficient organizational flexibility to adapt across governance levels [6,21]. This makes them structurally different from Western NGOs and from conventional state extension agencies, a distinction that existing adaptive governance theory does not theorize adequately [12,13].

External organizations integrate into rural societies through processes of social embeddedness. Granovetter's foundational framework [14] posits that economic action is shaped by social relationship networks, and that institutional effectiveness depends on an actor's ability to embed within local trust structures. In China's rural context, Sang and Li's concept of differential embeddedness [16] traces how exogenous organizations transition from outsiders to trusted partners through staged processes of social integration, providing a direct theoretical lens for understanding STB village-level dynamics.

2.2. Knowledge Intermediaries in China's Environmental Governance

Agricultural non-point source pollution has become a central challenge in China's water quality governance, driven by decades of intensive fertilizer application, livestock expansion, and inadequate rural wastewater management [3,4]. China's governance response has evolved from administratively dominated command-and-control approaches toward more adaptive, multi-stakeholder models that seek to balance ecological objectives with rural livelihood continuity [5]. A persistent structural challenge is the "last mile" problem—the difficulty of translating state environmental policies into locally appropriate practices without undermining the smallholder livelihoods that rural economies depend on [2]. Knowledge intermediaries have attracted growing scholarly attention as an institutional response to this challenge. These organizations facilitate the transformation of scientific knowledge into local practices, bridging the gap between research institutions and farming communities [21]. Critically, existing studies suggest that knowledge intermediaries do more than transfer technical information—they reshape governance relationships through trust building, coordination, and institutional translation across policy domains [25,26]. In China's specific governance context, university-based knowledge intermediaries occupy a privileged dual position: their embeddedness within the state system grants access to policymakers, while their sustained community presence enables grassroots knowledge translation. This dual positioning creates both opportunities and tensions in their governance roles that existing literature has not fully examined.

2.3. Science and Technology Backyards: From Technology Transfer to Social Integration

The Science and Technology Backyard model was first established in 2009 by Academician Zhang Fusuo's team at China Agricultural University in Quzhou, Hebei Province, and has since expanded to over 5000 sites nationwide. Early research focused on STBs' technical effectiveness. A landmark study published in *Nature* demonstrated that STBs significantly improved smallholder yields by narrowing yield gaps through participatory technology development [7]. Subsequent research confirmed STBs' value as university-based innovation intermediaries at the community level, documenting how their roles evolved from knowledge brokers to systemic innovation facilitators capable of supporting the co-evolution of technological, social, and institutional change [6]. More recent scholarship has shifted toward social and institutional dimensions. Li and Sang [16] proposed a framework of field relevance, differential embedding, and trust structure reproduction, showing that STBs' integration into local societies follows a differential rather than linear process across interest and emotional dimensions. Other studies have employed evolutionary game theory to examine STB-farmer-institution interactions, finding that STBs are highly sensitive to economic return structures [27]. From an adaptive governance perspective, Cai and Wang [28] identify a multi-level pathway through which social organizations activate endogenous rural governance capacity. However, across this body of work, a consistent gap remains about how STBs acquire and exercise institutional access within China's hierarchical governance system, and how this access shapes the distribution of governance benefits across different actor groups, has not been systematically examined. This gap defines the analytical contribution of the present study.

2.4. Research Gaps

Existing research has widely recognized the importance of knowledge intermediaries and bridging organizations in environmental governance. Knowledge intermediary theory focuses on how scientific knowledge is communicated, translated, and applied across different groups of actors, while bridging organization research highlights their role in coordinating stakeholders and integrating resources across organizational boundaries [19,20].

However, less attention has been paid to how such organizations gain access to formal governance systems and influence policy implementation in practice. Likewise, although adaptive governance scholarship emphasizes learning, feedback, and collaboration, it offers limited insight into how sustained interactions between the state and local communities are fostered in contexts characterized by strong state involvement [12,13].

Against this backdrop, this study does not aim to extend adaptive governance theory or knowledge-intermediary theory as independent, freestanding frameworks. Rather, it draws on both studies to support a single, original contribution: theorizing the Science and Technology Backyard as a distinct type of socio-technical institution, in which knowledge-intermediary research informs its technological dimension, social embeddedness theory informs its relational dimension, and adaptive governance scholarship informs its institutional-access dimension. We argue that the effectiveness of such an institution depends on the joint, rather than separate, operation of these three dimensions. Specifically, the study explores how the STB connects state policy objectives with local practices through three bridging mechanisms: technical correction, power adjustment, and market linkage. By doing so, this reframes the central research question: not whether STBs are effective knowledge intermediaries, but under what structural conditions socio-technical institutions produce uneven versus integrated governance outcomes, a question addressed empirically in Sections 4–6.

3. Governance Context and Village Differentiation

3.1. The Stages of Erhai Lake Governance

Erhai Lake, located in Dali Bai Autonomous Prefecture of Yunnan Province, is the second-largest freshwater lake in the province and serves as a critical ecological and livelihood foundation for surrounding communities [29]. Since the 1980s, rapid population growth and agricultural intensification across the basin have progressively increased ecological pressure on the lake, leading to deteriorating water quality and rising eutrophication risks [30]. The governance trajectory of Erhai Lake reflects a gradual but profound transformation across three interlinked phases, each marked by shifts in policy orientation, institutional design, and governance intensity.

The first phase, extending until around 2015, represents an early stage of regulatory foundation-building and localized ecological intervention. Formal governance began with the enactment of the Erhai Lake Management Regulations of Dali Bai Autonomous Prefecture in 1989, which established the first legal framework for lake protection. Although these regulations were progressively revised, governance capacity remained limited and largely reactive. Ecological crises, particularly the severe cyanobacterial blooms of 1996 and 2003, exposed the lake ecosystem's vulnerability and prompted public and governmental concern [30,31]. In response, local authorities implemented corrective measures focused on controlling direct human interference, including the elimination of cage fish farming, restrictions on motorized fishing, and ecological restoration programs such as the Three Retirements and Three Restorations, which converted farmland to forests, ponds to lakes, and residential land to wetlands. Despite these interventions, governance remained spatially concentrated around the lake shoreline, focusing on point-source pollution control while leaving broader basin-wide agricultural systems and rural livelihoods largely unaddressed [31].

The second phase, from 2015 to 2020, marks a decisive transition toward politically driven and highly intensified governance. A critical turning point occurred in 2015 when national leadership emphasized the ecological importance of Erhai Lake during an inspection visit to Gusheng Village, elevating its protection to a strategic political priority [32]. This top-level attention rapidly translated into escalating governance measures at provin-

cial and local levels. By 2016, emergency conservation protocols were activated. By 2017, Dali City had implemented a comprehensive regulatory package including strict controls on rural construction, suspension of housing approvals in ecological zones, demolition of illegal structures, and tightened regulation of tourism activities [32]. A defining feature of this phase was the Three Prohibitions and Four Promotions policy framework, which prohibited nitrogen and phosphorus fertilizers, highly toxic pesticides, and garlic cultivation, while promoting organic fertilizers, environmentally friendly pesticides, sustainable farming practices, and standardized livestock management [33]. Although these measures significantly improved water quality, they generated substantial socioeconomic disruption, dismantling traditional garlic-based farming systems, forcing rural tourism enterprises to close or restructure, and producing widespread livelihood insecurity that led in some cases to collective petitions [32,33]. By 2020, ecological conditions had improved notably, with water quality reaching Class III standards in many monitoring periods and occasionally Class II, marking a transition from emergency intervention toward more stabilized management [30].

The third phase, from 2020 to the present, reflects the emergence of a more systematic, knowledge-driven, and institutionally integrated governance regime. The approval of the Erhai Lake Protection and Management Plan (2018–2035) in 2020 signaled a shift toward long-term strategic planning based on spatial zoning, pollution source control, ecosystem restoration, and integrated basin governance, with a target of maintaining Class II water quality [32]. In 2021, governance further evolved through a multidimensional regulatory framework and the introduction of scientific and technological governance tools. A key institutional innovation was the establishment of a university-based Science and Technology Backyard in Gusheng Village, led by a research team from China Agricultural University under the leadership of Academician Zhang Fusuo of the Chinese Academy of Engineering. This marked a transition from purely administrative governance toward a hybrid model integrating scientific research, technological innovation, and policy implementation [6,7]. The STB developed a dynamic monitoring system for non-point source pollution, enabling precise tracking of nitrogen and phosphorus flows across the basin, and introduced integrated interception, purification, and reuse technologies that significantly reduced pollutant discharge. Concurrently, large-scale land transfer policies facilitated green ecological agriculture, while digital governance platforms integrated monitoring data, expert systems, and administrative decision-making. By 2025, these combined efforts had produced sustained water quality improvements, with most monitoring stations reporting Class II standards and no large-scale algal blooms over extended periods [30].

Overall, Erhai Lake governance has evolved from localized remediation to campaign-style intervention and finally toward a systematized, science-based governance model [2,5]. Within this transformation, the STB has shifted from a peripheral technical supporter to a central actor embedded in governance processes. Critically, however, this intensification of governance has simultaneously restructured rural production systems and livelihood structures across the basin, producing differentiated adaptation trajectories among villages that form the focus of the next section.

3.2. Village Type Differentiation Under Policy Shocks

The strengthening of Erhai Lake governance policies, particularly through land transfer mechanisms and the Three Prohibitions and Four Promotions framework, has fundamentally restructured the resource base and livelihood systems of villages within the basin [33]. However, this transformation has not been uniform. Due to variations in geographic location, resource endowment, and policy exposure, the six natural villages in the Gusheng area have differentiated into three distinct types: policy-driven transformation villages,

resource-endowment-based villages, and policy-constrained villages. This typology was not assigned a priori but derived inductively from fieldwork data and validated through triangulation across interviews, participant observation, and documentary sources [23]. Villages were differentiated according to four empirical criteria: (1) land transfer intensity, measured as the proportion of village arable land transferred to government or enterprise-led ecological and tourism projects; (2) agricultural dependence, indicated by the share of household income derived from farming; (3) ecological restriction level, based on whether the village falls within the core ecological corridor, the land transfer zone, or the Cangshan Mountain protection red line under Erhai governance policy; and (4) observed change in livelihood structure since 2017, such as shifts toward tourism, alternative cash crops, or off-village employment. These criteria were applied consistently across all six natural villages and cross-checked against village statistical records and local policy documents. Table 4 summarizes how each village type scores along these four dimensions. Engagement with the STB is deliberately excluded from the classification criteria and is treated in Section 5.2 as the outcome to be explained, so that village type, defined by antecedent conditions, and STB embedding intensity, the explanandum, remain analytically independent.

Table 4. Village Typology and Classification Criteria.

Village Type	Villages	Ecological Restriction Level	Agricultural Dependence	Resource Endowment	Livelihood Change Since 2017
Policy-driven transformation	Gusheng	High: core ecological corridor and land transfer zone	Medium to high: prior to policy heavily agricultural; now largely service-based	Moderate: flat land transferred; remaining assets tourism-linked	Near-complete shift from farming to homestay, catering, and tourism employment
Resource-endowment-based	Nanzhuang, Zhongzhuang, Beizhuang	Medium: fertilizer and crop restrictions apply; outside core transfer zone	Low to medium: continued farming but on restricted crop portfolio	High: flat terrain, stable irrigation, productive farmland retained	Shift from garlic and corn-cattle cycle to lettuce and fresh corn; high market price sensitivity
Policy-constrained	Yangxi, Beiyangxi	High: Cangshan Mountain ecological protection red line	High: historically dependent on farming and supplementary resource extraction	Low: mountainous terrain, limited irrigated farmland, restricted resource access	Increasing off-village employment; land leased in other regions for tobacco and vegetable cultivation

Source: Authors' fieldwork, 2025. Ratings are relative classifications derived from interview accounts, participant observation, and village statistical records rather than fixed numerical thresholds.

Gusheng Village represents the policy-driven transformation type, located within the core ecological corridor along the western shore of Erhai Lake. Large-scale land transfer policies and strict ecological zoning led to the near-complete withdrawal of traditional agriculture [32]. As land-based livelihoods disappeared, households shifted toward service-oriented activities, particularly homestay operations, catering, and tourism-linked employment. However, this transition was largely externally imposed rather than endogenously developed, leaving household incomes highly sensitive to fluctuations in tourism demand and external investment flows.

Nanzhuang, Zhongzhuang, and Beizhuang represent resource-endowment-based villages, characterized by relatively flat terrain, stable irrigation systems, and historically strong agricultural productivity. These villages retained land-use rights, allowing continued farming, but policy restrictions on fertilizers and certain crops disrupted established agricultural systems, particularly the traditional corn, cattle, and garlic production cycle [33]. Farmers responded by shifting toward alternative cash crops such as lettuce and fresh corn oriented toward national markets. However, these crops are highly sensitive to price fluctuations and market volatility, increasing livelihood uncertainty despite continued agricultural production [34].

Yangxi and Beiyangxi represent policy-constrained villages located near the Cangshan Mountain ecological protection zone. Historically dependent on supplementary livelihoods such as wild mushroom collection and small-scale resource extraction, these villages faced severe restrictions under ecological red line policies. Although large-scale land transfer did not occur, households increasingly sought livelihoods outside the village, including leasing land in other regions for tobacco and vegetable cultivation. This has resulted in spatially dispersed, fragmented livelihood strategies that differ markedly from those of both fully transformed and agriculturally stable villages [35].

These three village types illustrate that governance interventions have produced differentiated and uneven transformation pathways rather than uniform outcomes. These differences are not merely spatial but reflect varying degrees of policy pressure, resource constraints, and market integration, forming the essential context for understanding how the STB engages differently with different village communities, as examined in Sections 4 and 5 (see Table 4).

3.3. Structural Contradictions in Grassroots Governance

The grassroots governance system in the Gusheng area operates through a three-tier structure consisting of administrative villages, natural villages, and villager groups, a framework historically rooted in the commune brigade and production team system of the collective era and subsequently modified through successive institutional reforms [17,18]. Formally, administrative villages function as the lowest level of state administration responsible for policy transmission and coordination; natural villages serve as the primary units of rural settlement and social life; and villager groups represent the basic units of land ownership and local self-governance. This layered structure shapes the conditions under which external organizations such as the STB can operate, defining both the access points available and the institutional gaps they must navigate.

Despite this formal architecture, significant structural contradictions persist in practice. Natural villages constitute the core space of daily production and social interaction yet lack formal institutional status and stable fiscal support [18]. Village group leaders, though locally elected, receive minimal financial compensation, severely limiting their administrative capacity and reducing their practical role to occasional coordination rather than sustained governance functions. Administrative villages, in turn, face the challenge of governing increasingly complex and spatially dispersed rural populations following land transfers and livelihood diversification, making systematic household-level engagement structurally difficult [32].

These structural conditions create a persistent disconnect in governance transmission. Policy directives from higher levels frequently fail to reach households effectively, while grassroots concerns struggle to move upward through formal channels [2]. This governance gap not only weakens policy implementation but also constrains the operational reach of the STB. Although village officials generally recognize the value of the STB, engagement remains irregular and dependent on temporary coordination during training sessions or

field experiments rather than on institutionalized collaboration. At the natural village level, communication is further constrained by the absence of formal feedback channels, meaning that household-level knowledge, concerns, and implementation difficulties rarely reach the STB or government agencies in systematic form.

As a result, the last-mile problem introduced in Section 2 becomes not merely a knowledge-transfer challenge but a structural governance bottleneck [2,32]. The STB operates in a context where the formal governance infrastructure for reaching individual households is already weak, and where the informal relationships through which it compensates for this weakness are themselves unevenly distributed across village types. This structural context is essential for interpreting the asymmetric embedding patterns documented in Section 5 and for understanding why the STB's three bridging mechanisms, examined in the following section, produce differentiated rather than uniform governance outcomes.

4. The Triple Bridging Mechanism and Legitimacy Construction of the STB

Since its establishment in Gusheng Village in 2021, the STB has evolved into a distinctive governance actor in the Erhai Lake basin, operating at the intersection of state intervention, scientific expertise, and rural society [7]. Unlike conventional administrative governance, which relies on hierarchical command or market mechanisms driven by profit incentives, the STB serves as a hybrid intermediary that translates rigid environmental policies into socially embedded, technically feasible practices [19,21]. Its operational logic is best understood through three interdependent mechanisms: technical correction, power adjustment, and market linkage, which together constitute a socio-technical institution embedded within local governance.

The three mechanisms reported below were derived inductively rather than imposed deductively. Following the coding procedure introduced in Section 1.2, open coding of interview transcripts and field notes generated first-order concepts such as “pollution misunderstanding,” “trust in experts,” and “price instability” (Table 3); these were grouped through axial coding into second-order themes and ultimately aggregated, through iterative comparison and discussion between the authors, into the three mechanisms of technical correction, power adjustment, and market linkage. The mechanisms are not independent in practice: technical correction frequently supplies the empirical evidence that enables power adjustment, for example, the monitoring data underlying the renegotiated vegetable-cultivation directive discussed in Section 4.1, while power adjustment in turn creates the political space within which market-linkage initiatives such as branding projects can be attempted; Section 4.4 returns to this interdependence. Distinguishing the STB's specific contribution from the effects of concurrent government policy, market trends, and village-specific resource endowments is an inherent challenge of single-case ethnographic research, which we do not claim to fully resolve through causal inference. We attribute an outcome to the STB only where interview or documentary evidence explicitly identifies a specific STB action as the proximate trigger of a subsequent change; where an outcome plausibly reflects broader policy implementation or market conditions independent of STB activity, we describe it as context rather than as an STB effect. Table 5 reports this evidence base, together with the corresponding outcome and limitation, for each mechanism, and Section 7 returns to this attribution challenge as a methodological limitation.

Table 5. Bridging Mechanisms, Supporting Evidence, and Governance Outcomes.

Mechanism	Representative Evidence	Governance Outcome	Key Limitation
Technical Correction	Six vertical and seven horizontal” monitoring system; 40% nitrogen and 30% phosphorus input contribution finding; green rice yield increase of approximately 15%; scaling to 55,000 mu by 2024	Revision of pollution policy assumptions; shift from rigid area-reduction directives to precision input management; adoption of green cultivation practices	Monitoring data not independently verified by authors; attribution of outcomes to STB difficult to separate from concurrent government policy
Power Adjustment	STB Researcher A quotation on policy translation; drinking water conflict resolution through comparative water quality assessment; four-step dishwashing method as policy communication tool	Reduced implementation resistance; resolution of specific governance deadlocks; internalization of ecological norms among some farmer groups	Mediating role is conditional on political alignment; STB proposals not adopted when they conflict with broader political priorities; dependent on informal relationships rather than institutionalized channels
Market Linkage	Farmer A and smallholder group quotations on price volatility and cooperative needs; Erhai Rice Fragrance branding initiative; enterprise procurement agreements	Partial market recognition for green produce; selective connection of larger producers to premium channels	Structurally weak: cooperatives remain nominal; cold chain and grading infrastructure absent; no compensatory market institutions for policy-compliant produce; smallholders unable to meet volume thresholds independently

More fundamentally, the study’s aim is not to estimate the STB’s net causal effect on ecological or agronomic outcomes but to trace how STB-generated knowledge claims acquire governance authority. Reported figures such as pollution-contribution shares, yield gains, and adoption scale are therefore analyzed as claims whose production and circulation we document, not as independently validated measurements. Consistent with the framework in Section 6, we do not treat the concurrent state campaign as a confounder to be removed: because technical correction becomes governance-relevant only through its coupling with institutional access, strong administrative authority is part of the mechanism rather than a rival explanation to be excluded.

4.1. Technical Correction: Reconstructing Policy Rationality Through Scientific Evidence

The foundational mechanism of the STB lies in its capacity to generate scientifically grounded evidence that reconfigures how environmental problems are understood and governed. Through systematic field monitoring and experimental research, the STB shifts governance from experience-based judgment to data-driven rationality, thereby reshaping both policy design and implementation [7].

A key example is the establishment of a “six vertical and seven horizontal” monitoring system covering non-point source pollution across 4600 mu of farmland in the Gusheng area. This system enables continuous tracking of nitrogen and phosphorus flows through irrigation channels, farmland runoff, and drainage networks. Three years of monitoring produced a critical empirical finding: agricultural non-point source pollution contributes approximately 40% of total nitrogen input and 30% of total phosphorus input to Erhai Lake, substantially lower than the roughly 70 to 80% share previously assumed by local

authorities [33]. These figures refer specifically to nitrogen and phosphorus inputs rather than to a single share of total pollutant inflow. This discrepancy revealed that earlier governance strategies were based on incomplete empirical understanding, leading to overly rigid policy interventions. According to STB researchers and prefectural officials interviewed for this study, this evidence was invoked in the subsequent revision of policy: the earlier directive mandating a fixed reduction in vegetable-cultivation area was replaced with a more flexible strategy emphasizing optimized planting structures and precision input management. A prefectural official (GOV01) described this reassessment: “Before the STB’s monitoring data came in, we assumed agriculture was the dominant source of pollution, roughly 70 to 80 percent. Their figures showed around 40 percent for nitrogen and 30 percent for phosphorus. That changed how we thought about the problem. We realized our previous restrictions were based on an incomplete understanding, so we moved toward more targeted measures rather than just cutting across the board.” The revision itself is a matter of documentary record; our analysis concerns how STB evidence was mobilized within this process, not whether it was the sole cause of the change. In this sense, the STB does not simply implement policy but actively reconstructs the epistemic foundations upon which policy is made.

A similar dynamic is visible in the promotion of green rice cultivation technology. Through field experiments in Gusheng Village, the STB demonstrated that precision fertilization combined with ecological rotation systems could both reduce nitrogen loss and increase yields by approximately 15%. STB researchers reported that these results were treated as the basis for scaling green-rice practices, which STB records place at 55,000 mu by 2024. We report this figure as an STB claim that acquired policy traction rather than as an independently verified adoption estimate; the analytical point is how such figures come to function as authoritative within the governance process. The significance of this process lies not only in technological success but in the transformation of abstract ecological goals into measurable, replicable production practices. Two clarifications bound these claims. First, the pollution-contribution estimates, the yield-increase figure, and the adoption scale derive from the STB’s internal monitoring and field-experiment records as relayed by STB researchers; we did not have access to raw datasets and do not present these magnitudes as independently verified. Second, and by contrast, the process on which our analysis turns, namely that STB evidence was invoked to revise policy rationality, is corroborated beyond STB sources: the replacement of the fixed area-reduction directive is documented in policy records, and prefectural and municipal officials interviewed independently of the STB described acting on this evidence. We therefore treat the numerical magnitudes as authoritative claims whose governance uptake we analyze, while the underlying mechanism of knowledge-to-policy translation rests on triangulated, multi-source evidence.

4.2. Power Adjustment: The STB as a Buffer Zone in Governance Conflict

Beyond technical correction, the STB plays a crucial mediating role in managing tensions between state policies and rural livelihoods. The implementation of strict ecological regulations, particularly the prohibition on garlic cultivation and the use of chemical fertilizers, created direct conflicts between environmental objectives and household income structures [32]. In this context, the STB functions as a buffer institution that softens the coercive edge of policy implementation.

Rather than enforcing regulations, the STB translates them into scientifically justified and socially understandable narratives. A STB Researcher (STB02) stated: “We translate the country’s mandatory environmental protection policies into daily farming practices. For instance, to safeguard water resources in the Erhai Lake Basin, we teach farmers the ‘four-step dishwashing method’ to cut down chemical residues in domestic wastewater.”

Through visualised soil and water data, farmers can directly observe the ecological impacts of specific agricultural practices. This shifts policy compliance from external coercion to internalized understanding, thereby reducing resistance and friction [15,16]. A smallholder (SH02) mentioned in the interview: “At first, many villagers had strong complaints and were not inclined to listen to the government. However, researchers from the STB live in the village all year round. When they explain technologies and present concrete data, we find their words far more acceptable.” A village cadre (VC01) described the same dynamic from the implementation side: “Before the STB arrived, enforcing these environmental policies was extremely difficult. Farmers saw the restrictions as coming from above, and when we tried to explain the rationale, they didn’t trust us. With the researchers living in the village, that changed. They could sit with farmers, show them the data, and explain things in everyday language. That made my job much easier. I didn’t have to enforce as much, because the explanation came from someone they trusted, not just from the government.”

The STB also operates as a bidirectional communication channel. It conveys policy logic downward while transmitting livelihood concerns upward to local governments [2]. In the case of drinking water conflicts between the Cangshan River and Erhai Lake, the STB conducted comparative water quality assessments and presented empirical evidence demonstrating compliance with safety standards despite taste differences. This facilitated the establishment of localized water purification systems, resolving a potentially prolonged governance deadlock.

However, this mediating role is not without limits. In cases where technical solutions conflict with broader political or strategic priorities, such as precision fertilization for restricted crops, the STB’s proposals remain unadopted. This reveals an important boundary: while the STB can mediate perceptions of governance, it cannot override final political decision-making authority [17]. Its role is therefore best understood as a conditional buffer rather than a substitute for state power. Figure 2 illustrates this dual identity tension, mapping how the STB simultaneously positions itself as a state-aligned governance instrument and a community-embedded development actor, and how the mediation between these two roles shapes its power adjustment function.

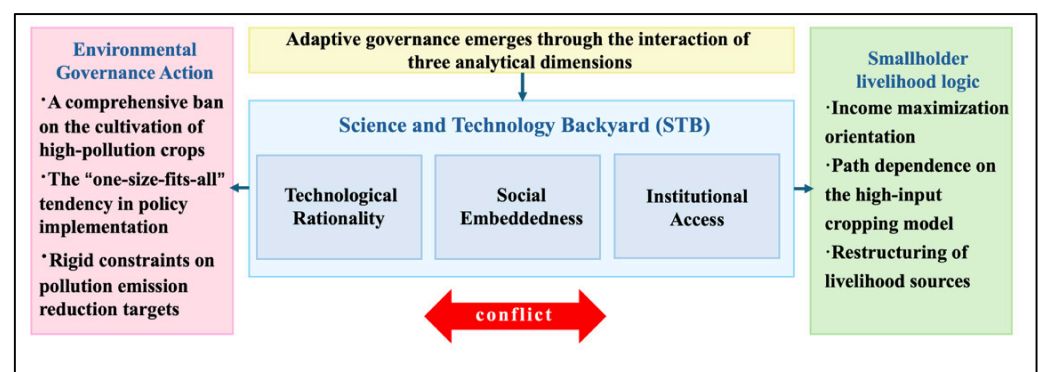


Figure 2. Dual Identity Tension and Mediation Model. The figure illustrates the STB’s simultaneous positioning as a state-aligned governance instrument and a community-embedded development actor, producing a structural tension that shapes its mediation.

4.3. Market Linkage: Partial Integration into Fragmented Rural Markets

The third mechanism through which the STB operates is market linkage, which aims to connect ecological governance with livelihood sustainability. While technical and regulatory interventions address production processes, market integration determines whether transformed agricultural systems can be economically viable [36].

The STB has initiated several attempts to construct value-added agricultural chains, including branded production of “Erhai Rice Fragrance” and green corn procurement agreements with premium pricing incentives. These initiatives have demonstrated partial success in building market recognition for ecologically produced goods and in incentivizing the adoption of green technologies.

However, the structural limitations of this mechanism are significant. Rural production in the basin remains highly fragmented, dominated by smallholders with limited scale, weak bargaining power, and unstable logistics systems [37,38]. The limitations of market linkage are not simply reflected in agricultural price fluctuations but are rooted in the weak institutional capacity of local market intermediaries. Compiled from interviews, a smallholder (SH03) from Gusheng Village stated: “Farmers like us have to go to the markets in Dali City ourselves to find sales channels, and the selling price of lettuce fluctuates wildly every year.” A group of smallholder farmers (SH04---SH06) similarly expressed: “We hope the STB can help set up an agricultural cooperative in our village. This would create better sales channels for our agricultural products, and we would no longer need to travel around to find buyers ourselves.” The cases of lettuce production illustrate this clearly: prices fluctuated from profitable levels to near-zero within a single harvest cycle, leaving farmers unable to recover production costs, as reported by multiple interviewed households.

The deeper institutional roots of this market linkage failure operate at three levels. At the cooperative level, rural cooperatives in the Gusheng area remain weakly institutionalized, functioning as nominal administrative entities rather than effective market organizations capable of aggregating supply, certifying quality, or negotiating prices [36]. Without functional cooperatives to pool smallholder output, individual farmers cannot meet the minimum volume thresholds required by enterprise buyers, and the STB’s branding initiatives therefore remain accessible only to larger-scale producers. An enterprise representative (ENT02) described the same constraint from the buyer’s side: “We recognize the quality of the produce, but as a buyer we need consistency: stable volumes, reliable quality, predictable supply schedules. Most farmers here are smallholders with fragmented plots, and they can’t guarantee the volume we require for a single order. We need co-operatives that can aggregate supply and maintain quality standards. The STB can help with the technical side and even with certification, but they can’t create the cooperative structures we need. That’s beyond their capacity.” At the supply chain level, the absence of cold chain logistics infrastructure and standardized grading systems means that even high-quality green vegetables cannot reliably reach premium urban markets at competitive prices, making product differentiation through branding structurally incomplete [35]. At the state–market interface level, the Erhai governance context creates a specific market distortion: ecological regulations have compressed the range of permitted crops while failing to establish compensatory market institutions such as green premium payment schemes or guaranteed purchase arrangements for policy-compliant produce [32]. The STB can partially compensate through information provision and branding support, but it cannot substitute for the formal market institutions whose absence is the fundamental cause of market linkage failure [36].

Not all STB initiatives encounter market-level obstacles; some face household-level resistance rooted in opportunity costs and livelihood rationality. Interviews with the head of the local STB revealed that rural women declined the STB’s proposal to help market woven handicrafts, concluding that the time required to produce them was not justified by the expected financial return. This illustrates that the STB’s influence has clear limits regardless of the mechanism through which it operates, and that farmer adoption ultimately depends on household-level opportunity costs, expected economic returns, and livelihood priorities [34].

These limitations point to a theoretical distinction that clarifies the legitimate boundaries of a knowledge intermediary. The obstacles the STB encounters in market linkage are of three analytically different kinds: information and knowledge gaps, coordination and brokerage gaps, and resource and institution-provision gaps. The first two fall within the intermediary's mandate, as the STB can supply agronomic and quality information, certify practices, convene actors, and broker connections between producers, enterprises, and the state. The third does not. Functioning cooperatives, cold-chain infrastructure, and compensatory payment schemes are not knowledge deficits but material and institutional endowments that require fiscal capital, regulatory authority, and organizational mandates the STB does not possess. Market linkage fails, in this sense, not because the STB brokers knowledge poorly but because the binding constraint in the economic domain is allocative and institutional rather than epistemic. This is the point at which the socio-technical institution reaches its structural ceiling: it can bridge governance, science, and society, but it cannot substitute for the state's allocative functions or the market's organizational ones.

This boundary reframes the question of accountability. To hold a university-based knowledge intermediary responsible for structural market failures of national scope would be a category error, mistaking an epistemic actor for an allocative or regulatory one, and would risk a form of responsibilities [39] in which the state's unmet obligation to build market institutions is transferred onto a research organization. The STB's accountability lies instead along axes proper to its role: the accuracy of its diagnosis, the avoidance of over-claiming that technical and branding interventions can resolve what are institutional deficits, and the transparent surfacing of the distributive consequences of its interventions, including the exclusion of smallholders documented in Section 5.3. A further axis follows from the STB's privileged brokerage position: because it can reach policy actors through the channels analyzed in Section 4.2, it is uniquely placed to escalate the diagnosis of missing compensatory institutions into governance channels, converting a market-failure observation into a policy signal. Read this way, market linkage is not simply the STB's weakest mechanism but the one that most clearly reveals the limits of knowledge-intermediation as a mode of governance: it marks where the scientific logic that grounds the STB's authority loses traction in an economic domain governed by capital and institutions rather than by evidence.

4.4. Integrative Logic: The Socio-Technical Institution as a Hybrid Governance Form

The three mechanisms described above are not independent but mutually reinforcing components of a broader institutional configuration. Technical correction provides epistemic authority; power adjustment generates trust and mediates institutional access; and market linkage tests the boundaries of socio-technical institutions in economic domains. Together, they form what this study conceptualizes as a socio-technical institution: an organizational form that embeds scientific knowledge within governance and rural society simultaneously [40,41].

Unlike traditional extension systems, which focus primarily on technology diffusion, or bureaucratic institutions, which rely on administrative authority, the STB operates through embedded interaction. Its legitimacy does not derive solely from the state or the market but from its ability to continuously align scientific rationality with local social realities [19,20].

At the same time, these dimensions are not balanced equally. Technical correction is the most institutionally consequential mechanism in this case because it operates within the STB's core epistemic domain and aligns with the state's demand for evidence-based governance. Power adjustment operates within clear boundaries set by political authority, and market linkage remains structurally weak because it requires institutional development

that lies beyond the STB's organizational mandate. This asymmetry is not incidental but reflects the broader institutional environment in which the STB operates, and it is examined in detail in Section 5.

In sum, the STB functions as a hybrid governance actor that simultaneously produces knowledge, mediates conflict, and experiments with market integration. Its significance lies not in any single function but in its ability to connect otherwise fragmented domains of governance, society, and economy, while remaining structurally constrained by the governance hierarchy within which it is embedded.

5. The Asymmetry of Integration: Multi-Level and Multi-Scalar Embedding of the STB

The integration of the STB into Erhai Lake governance is not a uniform or linear process but a structurally uneven form of embedding shaped by hierarchical governance logic, differentiated village conditions, and the internal logic of technological dissemination itself [12,13]. Across administrative levels, village types, and production structures, the STB exhibits a consistent pattern of asymmetry, revealing the institutional constraints of hybrid governance in rural China. This asymmetry is not a deviation from its function but a defining feature of how socio-technical institutions operate within multi-level governance systems [40,41].

5.1. Vertical Asymmetry: Strong Upper Levels, Weak Middle Layers, and Fragile Grassroots Embedding

Vertically, the interaction between the STB and government institutions demonstrates a pronounced stratification characterized by strong engagement at the top, functional but limited coordination in the middle, and weak institutional penetration at the grassroots level.

At the prefectural level, the STB benefits from direct political and epistemic coupling between academic authority and policy leadership. Through the academician and party secretary direct dialogue mechanism, research findings are rapidly translated into policy adjustments without significant bureaucratic delay [17]. Empirical evidence generated by the STB, such as revised estimates of non-point source pollution contributions, has directly influenced basin-wide regulatory planning. This reflects a high degree of epistemic alignment between scientific knowledge and top-level political decision-making, a dynamic facilitated by the institutional status of academician-level researchers within China's Party-state hierarchy.

At the municipal and township levels, interaction becomes primarily task-oriented rather than institutionalized. Local governments engage the STB as a technical service provider, mobilizing it to meet specific performance indicators such as pollution-reduction targets or demonstration project outputs. This is consistent with the prevailing logic of campaign-style governance and project-based governance in China's grassroots governance system [17,18]. While this facilitates implementation, it does not generate stable collaborative institutions. Instead, coordination remains episodic and dependent on administrative demand cycles rather than on structured, reciprocal engagement.

At the village level, particularly in natural villages and village groups, embedding becomes fragile and relies heavily on informal networks. Communication is often mediated by individual actors or temporary arrangements rather than institutionalized channels [2]. The absence of stable fiscal support, formal responsibilities, and structured feedback mechanisms limits the STB's ability to systematically engage with grassroots actors. As a result, governance transmission is interrupted at the last mile, where policy intent, technical knowledge, and local practice fail to converge consistently.

This vertical pattern reveals a central tension: while high-level political authority enables rapid policy translation, the absence of institutionalized mid-level and grassroots coordination prevents the STB from becoming a fully embedded governance infrastructure [32].

5.2. Horizontal Asymmetry: Differentiated Embedding Across Village Types

Horizontally, the STB exhibits a differentiated pattern of engagement across village types, reflecting variations in resource endowment, policy exposure, and livelihood restructuring pathways [16].

In Gusheng Village, the STB operates as a deeply embedded socio-technical hub. Given the extensive land transfers and the decline of traditional agriculture, its role extends beyond technological intervention to include social service provision, community support, and cultural integration. Daily co-living arrangements between students and villagers, combined with participation in local customs and cultural practices, produce a high level of social embeddedness [15,16]. In this context, the STB functions not only as a knowledge provider but also as a quasi-community actor embedded in everyday rural life.

In resource-endowment-based villages such as Nanzhuang, Zhongzhuang, and Beizhuang, the STB's role is more selectively technical. Engagement primarily occurs through demonstration fields, technical training, and cooperation with large-scale farmers. These actors serve as primary nodes for technology diffusion due to their capacity to absorb risk and implement standardized practices [37,38]. However, this also produces a structural concentration of benefits, as smallholders remain partially excluded from effective adoption pathways, a dynamic examined in detail in Section 5.3.

In policy-constrained villages such as Yangxi and Beiyangxi, interaction is minimal and episodic. Geographic distance, ecological restrictions, and limited integration into core governance priorities result in weak institutional presence [32]. Engagement is largely limited to occasional surveys or policy dissemination activities, producing only superficial awareness rather than substantive integration.

This horizontal differentiation produces a clear gradient of embedding intensity: strong in the core village, moderate in agricultural production zones, and weak in peripheral ecological villages. This pattern demonstrates that socio-technical institutions do not diffuse evenly but instead follow a centripetal model of spatial concentration, in which proximity to the STB's operational base, alignment with state governance priorities, and agricultural productive capacity together determine the depth of institutional engagement [40]. Figure 3 illustrates this differentiated embeddedness across governance levels and village types, and Table 6 summarizes the embedding intensity, key mechanism, and primary constraint for each category.

Table 6. Patterns of Asymmetric Embeddedness Across Governance Levels and Village Types.

Dimension	Category	Key Mechanism	Primary Constraint
Vertical—Administrative Level	Prefectural	Academician–party secretary direct dialogue; policy translation	None identified—high epistemic and political alignment
Vertical—Administrative Level	Municipal/Township	Task-based technical service; project performance targets	Episodic, project-dependent coordination; no stable institution
Vertical—Administrative Level	Natural Village/Village Group	Informal personal networks; occasional training sessions	Absent fiscal support; no formal feedback channel

Table 6. *Cont.*

Dimension	Category	Key Mechanism	Primary Constraint
Horizontal—Village Type	Policy-driven transformation (Gusheng)	Co-living; cultural participation; daily social interaction	High tourism sensitivity; externally imposed transition
Horizontal—Village Type	Resource-endowment-based (Nanzhuang, Zhongzhuang, Beizhuang)	Demonstration fields; technical training; large-farmer cooperation	Benefit concentration among large-scale farmers
Horizontal—Village Type	Policy-constrained (Yangxi, Beiyangxi)	Occasional surveys; policy dissemination	Geographic distance; ecological restrictions; limited STB presence
Internal—Farmer Type	Large-scale farmers	Pilot projects; nutrient monitoring system; branding initiatives	Risk of over-dependence on STB relationships
Internal—Farmer Type	Smallholder farmers	Indirect trickle-down from large farmers; nominal training inclusion	Land fragmentation; capital shortage; informal invitation only

Source: Authors' fieldwork, 2025. Embedding intensity assessed qualitatively based on interview accounts, participant observation, and documentary sources.

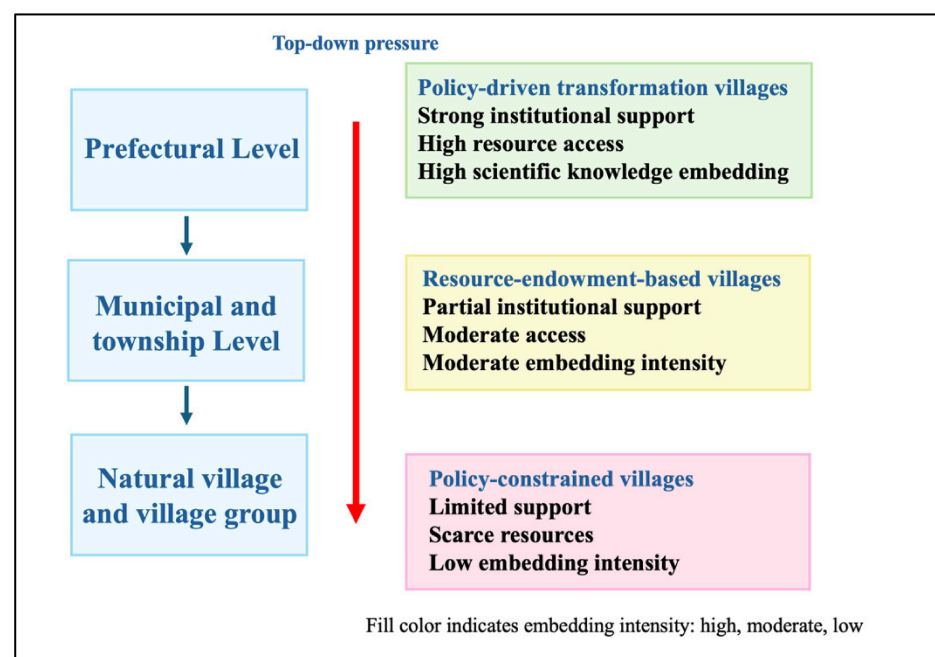


Figure 3. Differentiated Embeddedness in a Multi-level Governance System. The figure maps the gradient of STB embedding intensity across administrative levels and village types, from strong prefectural coupling through moderate township engagement to weak natural village penetration. The spatial and hierarchical patterns illustrated correspond to the empirical findings in Sections 5.1 and 5.2, and are further summarized in Table 6.

5.3. Structural Bias in Technology Diffusion: The Dominance of Large-Scale Actors

A third layer of asymmetry emerges within the internal logic of technology dissemination itself, where adoption pathways are structurally biased toward large-scale agricultural actors. Because this study did not administer a household-level survey, large-scale and smallholder actors are defined operationally through fieldwork observation and locally meaningful criteria rather than through a single statistically derived threshold. Following the class-analytic position that smallholders cannot be distinguished by cultivated area alone but by a bundle of attributes spanning land, capital, labor, and market relations [42],

we define the categories along three observable dimensions. Smallholders are households cultivating their original contracted allotments, typically fragmented, non-contiguous plots of approximately one to three mu, well below the national average household operational scale of approximately 0.5 hectares (about 7.8 mu) [42], relying primarily on family labor, with minimal fixed-capital investment and limited capacity to absorb production risk. Large-scale actors are households that have consolidated land through the basin's land-transfer market into contiguous parcels substantially exceeding the local average, enabling the fixed-capital investment, digital literacy, and risk tolerance that the STB's sensor-based demonstration model presupposes. The fifteen large-scale households connected to the STB through local-government coordination constitute the empirical referent for this category. This distinction is relational and context-specific: it identifies the structural point at which a household can meet the technical and capital preconditions of the STB's diffusion model, rather than asserting a universal land-area cutoff.

The STB's operational model relies on demonstrable efficiency, controllable risk, and measurable outcomes. These requirements naturally align with large-scale farmers who possess contiguous land, stronger capital reserves, and a higher tolerance for experimentation. As a result, they become the primary recipients and co-producers of technological innovation, particularly in pilot projects and commercialization pathways. Interviews with STB Researcher A indicate that the project has attempted to establish a large farmer-led and smallholder transformation technology diffusion mechanism. Through coordination with local government, the STB has established connections with 15 large-scale farming households and has further promoted advanced production technologies such as the nutrient monitoring system to these large-scale farmers, who then disseminate these technologies to smallholder farmers.

Three specific dimensions of this bias were observable in the Gusheng fieldwork.

First, regarding technology design and access, the nutrient monitoring system promoted to the STB's 15 connected large-scale households requires contiguous land parcels for sensor calibration, upfront installation investment, and digital literacy for data interpretation. For smallholder households operating fragmented plots of typically one to three mu, these requirements represent prohibitive barriers independent of willingness to adopt [37,38]. Smallholder farmers interviewed during fieldwork consistently indicated that they were unaware of the nutrient monitoring system's existence, and those who had heard of it described the cost and technical requirements as beyond their means. Several smallholders noted that the technologies promoted by the STB were generally perceived as more suitable for farmers with larger landholdings and greater capital rather than for households managing only a few mu. Fieldwork observations further confirm that STB demonstration fields were consistently located on large, contiguous plots managed by leading farmers, meaning the experimental conditions under which technologies were validated did not reflect the fragmented landholding reality of the majority of farming households in the basin.

Second, regarding training participation, farmer training sessions organized by the STB were primarily attended by large-scale farmers and village cadres, with smallholder attendance irregular and largely dependent on personal relationships with STB researchers rather than formal invitation structures. Smallholder farmers interviewed during fieldwork reported that they were seldom directly notified of upcoming training sessions, and several indicated that even when they attended, the content including precision fertilization scheduling, soil pH management, and ecological rotation protocols assumed a level of operational scale and capital availability that did not match their production conditions. As a result, even nominal inclusion in training activities did not translate into effective knowledge transfer or practical adoption for most smallholder households [34].

Third, regarding market linkage, the STB-facilitated Erhai Rice Fragrance branding initiative and enterprise procurement agreements were structured around minimum volume thresholds and quality certification standards that required consistent input management across a full growing season. Smallholder farmers reported during interviews that they found it difficult to meet these standards independently given their fragmented land and limited capital, and that without a cooperative structure to aggregate supply, participation in premium market channels remained effectively out of reach. Without such aggregation mechanisms, the market-linkage initiatives primarily benefited large-scale producers capable of meeting enterprise requirements, while smallholders continued to sell through volatile spot markets, as illustrated by the lettuce price fluctuations described in Section 4.3 [37,38].

These three dimensions constitute a structural rather than incidental form of exclusion. The bias does not arise from deliberate policy choices by the STB but from the operational logic of a knowledge-intermediary model optimized for demonstrable, scalable outcomes, a logic that is structurally misaligned with the fragmented, risk-averse production systems of most smallholder households in the basin. Externally promoted technologies are likely to encounter resistance or be abandoned if they cannot be embedded within local risk-management logics and everyday social relations [34]. China's agricultural technology diffusion system more broadly has contributed to improving modernization efficiency, but its reliance on leading farmers and large-scale producers has objectively accelerated the marginalization of vulnerable smallholders [43]. Given the absence of systematic household-level adoption or income data, these patterns are presented as qualitative findings derived from fieldwork observation and interviews rather than statistically verified outcomes, and they warrant further investigation through quantitative comparative research.

5.4. Theoretical Implication: Asymmetry as a Structural Feature of Socio-Technical Institutions

Across vertical governance levels, horizontal village differentiation, and internal diffusion mechanisms, a consistent pattern emerges: the STB does not produce uniform integration but rather stratified embedding. This asymmetry is not a temporary limitation but a structural characteristic of socio-technical institutions operating within hierarchical governance systems [40,41]. Table 6 provides a structured summary of this asymmetry across all three dimensions.

At its core, this reflects a fundamental tension between three logics [12,13]. Political logic prioritizes hierarchical implementation and performance accountability; scientific logic emphasizes experimentation and evidence-based adaptation; and social logic is grounded in localized trust, livelihood needs, and informal institutions. The STB operates precisely at the intersection of these logics, but it cannot fully reconcile their contradictions. Rather than achieving coherent integration across all three domains, it negotiates partial alignments that are necessarily uneven in their distribution of benefits and access [17,18].

Its integration pattern is therefore necessarily asymmetric. Embedding is strongest at the top, selective in the middle, and fragile at the grassroots; concentrated in core villages, partial in agricultural zones, and minimal in peripheral areas; and biased toward large-scale actors within production systems. Within this case, this pattern reflects structural conditions that may operate more broadly across university-based knowledge intermediaries in China's Party-state governance architecture; establishing this is a proposition for future comparative testing rather than a claim demonstrable from a single case [6].

In this sense, asymmetry is not a failure of integration but the operational condition under which socio-technical institutions function. It reflects both the enabling power and the structural limits of hybrid governance in contemporary rural China, and it raises

important questions about equity, inclusion, and the distribution of governance benefits that existing adaptive governance frameworks have not yet adequately theorized [12,13].

Table 7 summarizes the relationship between analytical dimensions, mechanisms, evidence, outputs, and governance outcomes.

Table 7. Analytical Framework Linking Dimensions, Mechanisms, Evidence, Outputs, and Outcomes.

Analytical Dimension	Core Analytical Logic	Bridging Mechanism	Representative Evidence (by Source)	Immediate Outputs	Governance Outcomes	Asymmetry Most Visible
Technological rationality	Scientific knowledge is translated into locally applicable farming practices through continuous experimentation and feedback.	Technical correction	STB researchers (STB02); government officials (GOV01); STB monitoring records and agricultural technical reports; field observation of demonstration plots and experiments	Revised pollution-source assessment; optimized fertilization schemes; improved farmer understanding of ecological farming	Evidence-informed policy learning; greater technical feasibility of environmental regulation	Vertical: strong prefectural uptake, weaker below
Social embeddedness	Long-term village residence and trust-building reduce implementation conflicts between government and farmers.	Power adjustment	STB researchers (STB02); smallholders (SH02); village cadres (VC01); government officials (GOV02); field observation of village meetings and training sessions. Negative case: irregular smallholder attendance at training relative to cadre and large-farmer participation	Increased communication between government and farmers; reduced resistance to environmental policy; greater willingness to participate	Improved coordination across administrative and community actors; enhanced adaptive governance capacity	Horizontal: differentiated by village type
Institutional access	Institutional legitimacy enables STB participation in policy implementation, while market coordination remains institutionally constrained.	Market linkage	Smallholders (SH03; SH04 to SH06); enterprise representatives (ENT02); STB researchers (STB03); policy documents on agricultural industrialization. Negative case: handicraft-marketing initiative declined by rural women on opportunity-cost grounds	Brand promotion; enterprise matching; limited expansion of market channels	Uneven market benefits; persistent dependence on formal market organizations; structural boundary of STB intervention	Internal: bias toward large-scale actors

Note: The three dimensions are cross-cutting properties present across all mechanisms; each row pairs a mechanism with the dimension it most directly expresses rather than an exclusive one. Evidence is reported by actor group with interview identifiers as listed in Table 2. Immediate outputs are the direct products of each mechanism; governance outcomes are their downstream effects.

6. Discussion: The STB as a Socio-Technical Institution

The preceding analysis demonstrates that the STB in Erhai Lake governance is not a simple technology transfer platform or a conventional extension institution, but a hybrid

governance formation that operates at the intersection of scientific knowledge production, state authority, and rural social organization [40,41]. Its significance lies not only in what it does but in how it reorganizes the relationship between technology, governance, and society. Building on this empirical foundation, this section develops a theoretical interpretation of the STB as a socio-technical institution, examines state-led adaptive governance in the Chinese context, and synthesizes the structural conditions under which socio-technical institutions produce uneven outcomes.

6.1. The Socio-Technical Institution: Extending Socio-Technical Systems into Governance Practice

From a theoretical perspective, the STB should be understood as a socio-technical institution: an organizational form in which technological rationality, social embeddedness, and institutional access are structurally integrated within governance processes. Recent socio-technical governance studies similarly emphasize that environmental transitions are not purely technological processes but institutional and relational reconfigurations embedded within governance systems [40]. While socio-technical systems theory emphasizes the co-evolution of technology and society [41], this study extends the framework in three directions that are necessary to capture the governance-specific dynamics observed in the Erhai case.

First, unlike classical socio-technical analysis that centers on technological transitions, the STB is fundamentally a governance intermediary [6,21]. Its primary function is not to introduce or diffuse technology as a standalone process but to translate policy objectives into implementable socio-technical arrangements. It operates as a bridge between state-led ecological mandates and locally grounded livelihood systems, embedding technological solutions within governance structures rather than externalizing them as market innovations [19,20].

Second, this study introduces institutional access as a distinct analytical dimension alongside technology and society, and argues that in China's governance context this dimension has no direct equivalent in Western socio-technical frameworks. The STB's legitimacy does not arise solely from scientific credibility or social acceptance but from its active integration into three specifically Chinese institutional structures. The academician and party secretary direct dialogue mechanism grants the STB privileged policy access through the institutional authority of an academic title within the Party-state hierarchy, bypassing normal bureaucratic channels in ways that boundary organization theory does not theorize [19,20]. Integration into Party-building activities at the village level generates political legitimacy and cadre relationships grounded in obligation and trust rather than professional or contractual logic. Strategic positioning within the project-based governance logic of township and county governments enables the STB to access resources and cooperation by aligning itself with administrative performance targets [17,18]. These three mechanisms constitute a form of institutional access that is empirically specific to China's Party-state governance architecture and analytically distinct from the institutional dimensions already present in socio-technical systems theory. These three mechanisms are not equally dependent on elite status. The academician and party-secretary direct dialogue is the highest-intensity and least generalizable form of institutional access, contingent on the political standing conferred by an academician title. Integration into village-level party-building and strategic positioning within project-based governance, by contrast, are channels available in principle to ordinary university research teams. Institutional access as an analytical dimension is therefore generalizable, even though its most direct instantiation in the Erhai case is not. This is also where the socio-technical institution concept earns its analytical keep. Knowledge intermediary, boundary organization, and hybrid governance actor each describe brokering across a boundary, but none specifies how

brokering is distributed within a hierarchical state. The socio-technical institution concept adds a testable proposition: where epistemic authority is coupled to institutional access within a Party-state hierarchy, embedding will be systematically asymmetric, strongest where scientific authority and state priority align and weakest at the grassroots and among smallholders. The asymmetry documented in Section 5 is evidence consistent with that proposition, which comparative work can test.

Third, while socio-technical systems theory is typically applied to long-term technological transitions, the STB operates within a compressed governance cycle shaped by administrative performance logic and policy urgency [17]. Its evolution is therefore not gradual and path-dependent but adaptive and interventionist, responding simultaneously to ecological crises, policy shifts, and livelihood disruptions.

Within this framework, the STB can be conceptualized as a structured integration of three mutually reinforcing dimensions. The technological dimension provides epistemic authority through scientific monitoring, experimentation, and evidence generation. The social dimension produces legitimacy through long-term interaction, cultural translation, and trust-building within rural communities, illustrated concretely by smallholder farmers borrowing pesticide sprayers from STB students as a form of informal trust-based exchange, and by STB researchers conducting training sessions in the Bai language as evidence of cultural embeddedness in knowledge dissemination. The institutional dimension secures policy relevance through formalized access to governance hierarchies. These three dimensions are not additive but interdependent: technological outputs without social embedding lack legitimacy; social relations without institutional access lack policy durability; and institutional positioning without technological credibility lacks authority.

6.2. Adaptive Governance in the Chinese Context

Adaptive governance is commonly understood as a process in which multiple stakeholders continuously adjust governance strategies through learning, negotiation, and feedback [8,9]. Most existing studies draw on Western experiences and emphasize the role of local communities, non-governmental organizations, and other non-state actors, associating adaptive governance primarily with bottom-up collaboration and decentralized decision-making [12,13]. However, the Erhai Lake case suggests that adaptive governance can emerge through a fundamentally different pathway in contexts where the state plays a dominant role.

Environmental governance in the Erhai Lake Basin is strongly shaped by state-led ecological priorities. As a nationally important ecological protection area, the basin is governed through hierarchical policy frameworks aligned with China's broader ecological civilization agenda [5,32]. In this setting, the definition of governance goals, the allocation of policy resources, and the design of regulatory frameworks are largely guided by government authorities rather than negotiated through pluralist stakeholder processes.

Our findings show, however, that strong state involvement does not prevent adaptive governance from emerging. The STB has created a structured channel of interaction between state institutions and local communities that generates genuine policy learning and adjustment [28]. Through long-term village engagement, participatory experimentation, and ongoing technical support, the STB translates scientific knowledge into locally adoptable practices while conveying farmer concerns and implementation challenges back to government agencies. The revision of the vegetable cultivation directive based on STB monitoring data and the resolution of the drinking water conflict through STB-facilitated quality assessment both illustrate this bidirectional feedback dynamic operating within a state-led governance framework.

The Erhai case therefore reveals a form of adaptive governance that is qualitatively distinct from community-centered models in the literature [8,9]. The state continues to set policy priorities and allocate resources, while governance adaptability emerges through structured interaction and mutual learning among government actors, scientific experts, and local communities, with the STB serving as the key intermediary. This broadens current understandings of adaptive governance by demonstrating that, under certain institutional conditions, effective collaboration between state actors, scientific expertise, and local knowledge can generate adaptive and responsive environmental governance without reducing state authority [12,13]. The enabling condition, as the Erhai case demonstrates, is the presence of a knowledge intermediary that simultaneously holds institutional access to the state and social embeddedness in the community.

6.3. Synthesis: The Structural Condition of Socio-Technical Institutions

The analysis suggests that the STB should be understood as a structurally constrained yet functionally adaptive socio-technical institution. Its effectiveness arises from its ability to align technological rationality, social embeddedness, and institutional access within a single organizational form. However, this alignment is inherently unstable and uneven, and the conditions under which it holds are context-specific.

Rather than representing a fully coherent governance model, the STB reflects a negotiated equilibrium between competing logics: state control and social autonomy, scientific optimization and livelihood security, and efficiency and equity [12,13]. Its contributions are therefore best understood not in terms of complete governance resolution but in terms of partial coordination across fragmented systems. This distinguishes it from both idealized adaptive governance models, which assume pluralist stakeholder participation, and from conventional extension agencies, which assume hierarchical implementation capacity.

The structural conditions that enable the STB's socio-technical institution function are three-fold. First, the presence of academician-level scientific authority creates a legitimate entry point into China's political hierarchy that ordinary research institutions or NGOs do not possess. This condition is also the least replicable. The STB model as a socio-technical form has diffused to more than 5000 sites nationwide, the majority led by ordinary faculty and graduate students, which indicates that its technological and social-embedding dimensions are broadly transferable. The direct prefectural-level policy access documented here, however, depended jointly on academician-level authority and the exceptional political salience of Erhai Lake, and is not generalizable to non-academician-led teams. This stratification of access is not incidental to the argument but is the mechanism underlying the vertical asymmetry documented in Section 5.1, in which policy influence is strong at the prefectural level and progressively weaker below it. Ordinary teams, lacking the elite channel, would necessarily rely on the slower project-based and grassroots routes, and would therefore be expected to exhibit an even more pronounced version of this asymmetry. Second, the co-living and community engagement model generates the social embeddedness necessary for knowledge translation, trust-building, and cultural legitimacy. Third, the project-based governance logic of China's administrative system creates periodic windows of opportunity for the STB to align its activities with state performance priorities and thereby secure resources and cooperation. Where any of these conditions is absent or weakened, as illustrated by the township-level coordination gap and the peripheral village disengagement documented in Section 5, the STB's effectiveness declines accordingly.

In this sense, the STB does not resolve the contradictions of rural ecological governance but reorganizes them into a manageable and persistent form of structured tension. This insight contributes to understanding how knowledge intermediaries can support adaptive governance within state-led systems and may offer cautious analytical reference for similar

contexts in rural China where university-based intermediaries operate alongside strong administrative hierarchies. Whether these dynamics extend to other national contexts remains an empirical question for future comparative research.

7. Conclusion, Policy Implications, Limitations, and Future Research

This study examined the role of the STB as a socio-technical institution within the multi-level governance system of Erhai Lake, focusing on how it mediates between state-led ecological governance and rural livelihood systems in a single ethnographic case. The findings show that the STB functions not as a conventional technology extension mechanism but as a hybrid governance actor that integrates scientific knowledge production, social embedding, and institutional mediation across fragmented governance scales.

A central conclusion is that the STB's governance effectiveness is structured through three interrelated mechanisms: technical correction, power adjustment, and market linkage. Among these, technical correction is most institutionally consequential in this case, as scientific monitoring and field experimentation have directly reshaped policy understanding and improved ecological governance outcomes. Power adjustment plays a stabilizing role by reducing conflicts between restrictive environmental policies and livelihood needs. Market linkage remains comparatively weak due to structural deficits in cooperative development, supply chain infrastructure, and state–market coordination that exceed the STB's organizational mandate.

A second key finding is the pronounced asymmetry in its embedding process. Vertically, the STB is closely connected to prefectural-level decision-making through academician and party leadership direct dialogue, but its influence weakens significantly at the township and village levels where institutionalized collaboration is limited and informal mediation predominates. Horizontally, its influence is concentrated in core transformation villages, partially present in resource-endowed agricultural villages, and weak in peripheral ecological protection zones, following a centripetal model of spatial concentration. Internally, technology diffusion is structurally biased toward large-scale agricultural actors, with small-holder households facing systematic exclusion within this case from technology design, training participation, and market-linkage initiatives.

A third conclusion is that this asymmetry is not incidental but structural, reflecting the operational logic of a knowledge-intermediary model optimized for demonstrable, scalable outcomes within a hierarchical governance system. The STB's effectiveness depends on the joint operation of technological rationality, social embeddedness, and institutional access; where any of these dimensions is weak, effectiveness declines accordingly.

Given the single-case design, these conclusions are presented as context-specific findings rather than generalizable propositions. The study nonetheless offers useful insights into how knowledge intermediary organizations can support governance adaptation and policy implementation within strongly state-led governance systems.

7.1. Policy Implications

The findings of this study generate three policy implications specific to the Erhai Lake governance context and analogous state-led ecological governance settings in rural China.

First, the pronounced vertical asymmetry identified in Section 5.1, where STB influence is strong at the prefectural level but weak at township and village levels, points to the need for institutionalized mid-level coordination. County and township governments, as the administrative actors responsible for translating prefectural policy into village-level implementation, are best positioned to formalize this role. A feasible step would be designating township-level science and technology liaison officers with defined responsibilities for mediating between STB outputs and local administrative processes. This would reduce

the current dependence on informal relationships and episodic project-based engagement, which the fieldwork identified as the primary reason governance transmission breaks down at the grassroots level.

Second, the structural exclusion of smallholder farmers documented in Section 5.3 calls for targeted adjustments to the STB's technology design and training delivery. The STB itself, in coordination with Dali City's agricultural bureau, could pilot modular, low-cost versions of existing technologies such as simplified soil-monitoring tools calibrated for plots under five mu, and restructure training invitations to reach smallholder households directly rather than through leading farmer intermediaries. Complementary subsidy instruments administered through the agricultural bureau could further reduce adoption barriers. These adjustments are feasible within the existing STB operational framework and do not require new institutional creation.

Third, the persistent weakness of market linkage identified in Section 4.3, reflected in lettuce price volatility and smallholders' inability to access premium procurement channels, points to the need for cooperative development as a structural complement to the STB's knowledge-intermediary function. Local governments at the township level, together with Dali City's rural revitalization office, are the appropriate actors to facilitate cooperative registration and governance. Minimum price guarantee arrangements for certified green produce, negotiated between cooperatives and enterprise buyers with government facilitation, represent a feasible instrument to stabilize smallholder incomes during ecological transition periods. Fiscal transfer payments targeting villages in ecological restriction zones, where governance costs are concentrated but benefits are diffuse, would additionally address the spatial inequity in cost distribution documented across the six natural villages.

7.2. Limitations and Future Research

This study has seven main limitations. First, it is based on a single-case design focused on Erhai Lake, limiting the transferability of findings to other ecological or institutional contexts. Second, the analysis relies primarily on qualitative interviews and observational data, with limited integration of long-term quantitative datasets such as household income dynamics or longitudinal ecological indicators. Third, the study captures a specific governance phase and does not fully examine the long-term sustainability of the STB in the face of potential institutional or political shifts. Fourth, because the STB operates alongside broader Erhai governance reforms and shifting agricultural markets, the qualitative evidence used to attribute outcomes to the STB's mechanisms cannot fully substitute for a quasi-experimental or comparative design; this attribution challenge is addressed through evidence triangulation in Table 5 but is not eliminated by it. Fifth, the authors' affiliation with China Agricultural University, the institution that established the STB model, creates a positionality risk that may have shaped how the STB presented its work to the research team despite the mitigation strategies described in Section 1.2. Sixth, the most direct institutional-access mechanism observed in this case, the academician and party-secretary direct dialogue, depends on elite scientific status and is not readily available to ordinary university research teams. The transferability of the STB model as a socio-technical institution is therefore bounded: while its technological and social-embedding dimensions are broadly replicable, its highest-level policy-access channel is not, and replication by non-academician-led teams would likely operate through weaker and slower institutional routes. Seventh, coding was carried out by a single researcher rather than through independent double-coding, with analytical consistency supported by co-author review of the coding framework and category boundaries.

Future research should address these limitations in two directions. Comparative studies across multiple lake basins such as Taihu, Dianchi, and Chaohu could assess

the transferability of the socio-technical institution model across different governance regimes and test whether the three structural conditions identified here—academician-level access, co-living embeddedness, and project-based alignment—are necessary or sufficient for knowledge intermediary effectiveness. Longitudinal research tracking village-level livelihood trajectories and ecological outcomes over time would additionally provide deeper insight into whether the STB produces durable institutional change or remains dependent on project-based governance cycles.

Author Contributions: Conceptualization, N.A.K.; methodology, N.A.K.; investigation, K.G. and S.X.; formal analysis, K.G. and N.A.K.; writing—original draft preparation, K.G.; writing—review and editing, B.A.A.; supervision, B.A.A.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Social Science Fund of China, Youth Project “Research on the Practical Path of Smallholder Farmers Integrating into the Modern Agricultural Management System under the Background of Rural Revitalization” (Grant No. 22CSH036), and the National Social Science Fund of China Key Project “Research on the Mechanism Linking Smallholder Production with Agricultural Modernization” (Grant No. 23ASH007). The authors extend their appreciation to the “Ongoing Research Funding Program (ORF-2026-443), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: This study was exempt from formal ethical review under the institutional requirements of China Agricultural University, which does not require ethics committee approval for non-interventional social science research involving voluntary adult participation and no collection of sensitive personal information. All participants were informed of the research purpose, the voluntary nature of their participation, and their right to withdraw at any time prior to the interview. Oral informed consent was obtained from all participants before each interview was conducted. All interview quotations reported in the manuscript have been anonymized using coded identifiers such as SH01, VC01, and STB01, as listed in Table 2. Potentially identifiable personal information was removed during transcription and analysis to protect participant confidentiality.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw interview transcripts and field notes underlying this study are not publicly available due to participant confidentiality commitments and the sensitivity of local governance content. To support research transparency, the following data-processing materials are available on request from the corresponding author: the semi-structured interview guide used during fieldwork; the anonymized coding framework presented in Table 3; the mechanism-evidence-outcome table presented in Table 5; and a description of the data-processing and thematic analysis procedure detailed in Section 1.2.

Acknowledgments: The authors would like to thank all interviewees and local participants involved in the field research. The authors extend their appreciation to the “Ongoing Research Funding Program, (ORF-2026-443), King Saud University, Riyadh, Saudi Arabia.”

Conflicts of Interest: The authors declare no conflicts of interest.

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