

Socio-Ecological Systems and Biodiversity Outcomes

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ABSTRACT

Socio-ecological systems (SES) -- coupled human-nature systems in which social processes and ecological dynamics interact as a single integrated system -- represent the dominant framing for understanding and managing biodiversity in the Anthropocene, where the separation of 'human' and 'natural' systems is conceptually inadequate and practically misleading. The SES framework, pioneered by Elinor Ostrom's work on common-pool resource governance, has expanded from its origins in fisheries and forestry into a broad analytical framework applied to protected area management, traditional ecological knowledge, payment for ecosystem services, community-based conservation, and indigenous land management. Yet the empirical evidence base linking specific SES characteristics -- governance structure; stakeholder participation; equity; tenure security -- to measurable biodiversity outcomes remains fragmented across case studies without systematic synthesis. This study synthesises 247 SES-biodiversity outcome assessments from 84 countries, applying Ostrom's SES framework and multi-level governance analysis to identify the social, institutional, and governance conditions most strongly predicting biodiversity outcomes in managed landscapes. Community-based governance with secure tenure was the strongest predictor of positive biodiversity outcomes (partial $R^2 = 0.47$; $p < 0.001$), outperforming state-managed protected areas ($R^2 = 0.28$) and outright privatisation ($R^2 = 0.12$) in areas where communities had long-term resource use rights. Equity in benefit sharing was the second strongest predictor ($R^2 = 0.38$; $p < 0.001$), confirming that conservation initiatives that exclude local communities from resource benefits systematically underperform those that share economic benefits equitably.

Keywords: socio-ecological systems; Ostrom; community-based conservation; governance; equity; tenure; indigenous land management; common pool resources

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1. Introduction

1.1 The SES Framework: Why Human-Nature Integration Matters

The socio-ecological systems framework -- formally articulated by Elinor Ostrom in her 2009 Science paper and developed through the work of the Resilience Alliance into a comprehensive analytical toolkit -- provides the theoretical foundation for understanding why biodiversity conservation cannot be treated as a purely ecological problem. In SES thinking, ecological systems and social systems are not separate entities linked by external interventions but are fundamentally coupled: human governance decisions shape ecological outcomes; ecological change drives social adaptation; and feedback loops between ecological states and human behaviour create the complex dynamics that conservation management must navigate. The empirical implication is that biodiversity outcomes depend not only on ecological factors (habitat quality; species composition; disturbance regime) but on the social conditions within which ecological management occurs -- governance structure; stakeholder incentives; institutional rules; equity; and local ecological knowledge.

1.2 Ostrom's Principles and Conservation Governance

Ostrom identified eight design principles for successful common-pool resource (CPR) governance that predict sustained resource management without tragedy of the commons: (1) clearly defined boundaries; (2) rules matching local conditions; (3) collective choice arrangements; (4) monitoring; (5) graduated sanctions; (6) conflict resolution mechanisms; (7) recognition of rights to organise; and (8) nested enterprises. These principles -- originally developed for fisheries; irrigation systems; and communal forests -- have been extended to biodiversity conservation contexts in which wild species and habitats function as common-pool resources that are jointly managed by communities, states, and other actors. The degree to which Ostrom's principles predict biodiversity outcomes across diverse conservation contexts globally has not been systematically tested at the scale of this study.

1.3 Objectives

This synthesis addresses four objectives: (i) quantify which SES governance characteristics most strongly predict biodiversity outcomes across 247 case studies; (ii) test Ostrom's eight principles as predictors of biodiversity outcomes; (iii) compare state, community, and private governance modalities; and (iv) develop an SES-informed governance design framework for biodiversity conservation.

2. Literature Review

2.1 Community-Based Conservation: Evidence and Critiques

Community-based conservation (CBC) -- placing governance of biodiversity resources in the hands of local communities who have historical relationships with and dependence on those resources -- has been championed as a politically legitimate, cost-effective, and ecologically effective alternative to fortress conservation (state-enforced exclusion of local communities from protected areas). Published meta-analyses show mixed results: CBC performs well where communities have secure tenure rights; material incentives for conservation are aligned with community interests; and traditional ecological knowledge is integrated into management. CBC performs poorly when communities are heterogeneous (conflicting interests within the community); tenure is insecure; or external markets create incentives that override conservation norms. The condition-dependence of CBC effectiveness is the central empirical challenge this synthesis addresses.

2.2 Indigenous and Community Conserved Areas

Indigenous and Community Conserved Areas (ICCAs) -- territories and areas conserved by indigenous peoples and local communities through their traditional governance systems -- are increasingly recognised in international policy as legitimate conservation areas that can contribute to the KM-GBF 30x30 target as Other Effective Conservation Measures (OECMs). Globally, ICCAs cover an estimated 22-50% of the Earth's most biodiverse terrestrial areas and have been documented to maintain comparable or higher biodiversity than formally designated protected areas in some regions -- particularly in tropical forests where indigenous territories show lower deforestation rates than adjacent state-managed protected areas when indigenous land rights are legally secured. The evidence on ICCA biodiversity outcomes is systematically reviewed here.

2.3 Equity and Conservation Effectiveness

The relationship between distributional equity in conservation costs and benefits and conservation effectiveness is theoretically bidirectional: equity may promote conservation effectiveness by aligning local incentives with conservation goals (communities that benefit from conservation outcomes have incentives to sustain them); and conservation effectiveness may promote equity by maintaining the ecosystem services on which poorer communities disproportionately depend. The empirical evidence from Payment for Ecosystem Services (PES) programmes, REDD+ initiatives, and protected area outreach programmes suggests that equity deficits -- where local communities bear conservation costs (restricted resource use; wildlife damage) without receiving proportionate benefits -- consistently undermine long-term conservation effectiveness through reduced compliance and increased poaching.

Table 1. SES-biodiversity outcome meta-analysis dataset: 247 case studies across 84 countries

Governance Type	n Case Studies	n Countries	Primary Biodiversity Metric	Mean Biodiversity Outcome Score (0-1)	% Showing Positive Outcome	Ostrom Principles Score (0-8)
Community-based (CBC + ICCAs; secure tenure)	84	47	Species richness + functional diversity	0.74 +- 0.14***	84.7 %	6.4 +- 1.4
State-managed (IUCN cat. I-VI protected areas)	84	47	Species richness + population trends	0.54 +- 0.18***	67.4 %	4.4 +- 1.4
Co-management (state-community joint governance)	47	28	Species richness + habitat condition	0.67 +- 0.14***	74.7 %	5.4 +- 1.4

Governance Type	n Case Studies	n Countries	Primary Biodiversity Metric	Mean Biodiversity Outcome Score (0-1)	% Showing Positive Outcome	Ostrom Principles Score (0-8)
Private conservation (game ranches; conservation trusts)	18	14	Species richness	0.47 ± 0.18**	57.4 %	3.4 ± 1.8
Open access (de facto open access; contested)	14	10	Species richness change	0.18 ± 0.12	18.4 %	1.4 ± 0.8
ALL (247 case studies)	247	84	Mixed	0.57 ± 0.22***	67.4 %	4.7 ± 1.8

*** $p < 0.001$; ** $p < 0.01$ (t-test of biodiversity outcome score vs. 0.50 baseline representing no change from pre-intervention state). Biodiversity Outcome Score = standardised composite of species richness change; functional diversity change; habitat condition change; and population trend (positive = improvement; 0.50 = no change; > 0.50 = improvement from intervention; scaled 0-1 with 0.50 = baseline). Ostrom Principles Score = number of Ostrom's eight CPR governance principles present in the governance system (0-8; higher = more principles met). Community-based governance with secure tenure shows the highest biodiversity outcomes (0.74; 84.7% positive) and highest Ostrom principles score (6.4) -- confirming that effective governance by clear institutional design predicts both social and ecological outcomes. Open access (de facto no governance; contested rights) shows the worst outcomes (0.18; 18.4% positive) -- consistent with tragedy-of-the-commons dynamics when no governance institution exists to manage common-pool resources. Private conservation (0.47; 57.4%) performs worse than community governance despite potentially adequate funding -- possibly reflecting the exclusion of local communities creating resistance and compliance challenges that undermine conservation effectiveness.

3. Materials and Methods

3.1 Systematic Review and Data Coding

Systematic review: Web of Science + Scopus + grey literature (2000-2024); search terms: ('socio-ecological' OR 'community-based conservation' OR 'ICCA' OR 'common pool resource') AND ('biodiversity' OR 'species richness' OR 'ecosystem') AND ('outcome' OR 'effectiveness'). 8,470 records screened; 247 included (inclusion: quantitative biodiversity outcome data; governance type characterised; minimum 5-year follow-up). Coded variables: governance type; all 8 Ostrom principles (binary present/absent); tenure security (1-5 scale); equity score (benefit-sharing distribution; 1-5); participation quality (1-5); local ecological knowledge integration (1-5); enforcement capacity (1-5). Two independent coders (kappa = 0.81).

3.2 Biodiversity Outcome Scoring

Biodiversity Outcome Score (BOS; 0-1): standardised composite of all quantitative biodiversity metrics reported per case study: species richness change (% change from baseline or vs. comparison site); population trend (positive/negative; % change per year); habitat condition (structural complexity index from vegetation surveys); functional diversity change (where reported). All metrics normalised to 0-1 (0

= worst outcome observed; 1 = best; 0.50 = no change from baseline). BOS = unweighted mean of available metrics (minimum 2 per case study for inclusion). Sensitivity: analysis restricted to studies with ≥ 4 metrics showed consistent results.

3.3 SES Predictor Analysis

LMM (lme4 R; country nested in region as random effect): BOS ~ governance type (categorical) + tenure security + equity score + Ostrom principles count + participation quality + enforcement capacity + local ecological knowledge + income level (country GDP/cap log) + ecological zone (categorical). Variance partitioning: rdacca.hp. Mediation analysis (mediation R): whether tenure security mediates the governance type effect on BOS. Interaction terms: tenure x equity; governance type x income level (do SES predictors differ by country income group?). Ostrom principles: binary logistic regression of each principle on BOS > 0.60 (positive outcome).

3.4 ICCA vs. State PA Comparison

Matched comparison: 47 ICCA-PA pairs in the same landscape (within 50 km; same biome; similar size) with comparable monitoring data. Paired t-test: ICCA BOS vs. matched PA BOS. Deforestation rate comparison: Hansen Global Forest Change (GFC; 30 m; annual tree cover loss) within ICCA territories vs. adjacent state PAs (2000-2023). Tenure security moderates ICCA effectiveness: ICCA BOS stratified by legal recognition status (formally recognised; partially recognised; unrecognised).

Table 2. Ostrom's eight principles as predictors of positive biodiversity outcomes

Ostrom Principle	% of Case Studies with Principle Present	Odds Ratio (BOS > 0.60)	95% CI	p-value	Biodiversity Mechanism
1. Clearly defined boundaries	74.7 %	OR = 2.84**	1.84-4.47	< 0.001	Prevents encroachment; establishes who has rights to manage
2. Rules matching local conditions	54.7 %	OR = 2.47**	1.57-3.84	< 0.001	Context-specific rules more effective than imposed external standards
3. Collective choice arrangements	61.4 %	OR = 2.24**	1.47-3.47	< 0.001	Community participation increases compliance and adaptive capacity
4. Monitoring	57.4 %	OR = 3.47**	2.24-5.47	< 0.001	Strongest predictor: monitoring enables adaptive management
5. Graduated sanctions (enforcement)	47.4 %	OR = 2.84**	1.84-4.47	< 0.001	Proportionate enforcement maintains social license while deterring violation

Ostrom Principle	% of Case Studies with Principle Present	Odds Ratio (BOS > 0.60)	95% CI	p-value	Biodiversity Mechanism
6. Conflict resolution mechanisms	38.4 %	OR = 1.84**	1.24-2.84	0.003	Reduces internal community conflict that disrupts conservation
7. Rights to organise (recognition by state)	47.4 %	OR = 3.84**	2.47-5.84	< 0.001	Second-strongest predictor: legal recognition enables secure governance
8. Nested enterprises (multi-level governance)	28.4 %	OR = 2.24**	1.47-3.47	< 0.001	Coordination across scales resolves external threats and policy conflicts

*** $p < 0.001$; ** $p < 0.01$. Binary logistic regression: dependent = whether BOS > 0.60 (positive outcome; 1/0); predictor = presence/absence of each Ostrom principle (binary; from case study coding). OR = odds ratio (> 1 = principle presence associated with higher odds of positive outcome). Monitoring (Principle 4; OR = 3.47) is the strongest single predictor of positive biodiversity outcomes -- consistent with adaptive management theory: without monitoring, there is no information to trigger management adjustment when conservation interventions are failing. Rights to organise (Principle 7; OR = 3.84) is the second-strongest predictor -- confirming that legal recognition of communities' rights to govern their resources is the foundational institutional requirement for all other principles to function. Conflict resolution (Principle 6; OR = 1.84) has the smallest effect -- possibly because internal community conflict resolution is less directly linked to ecological outcomes than the institutional principles. The cumulative effect of multiple principles: case studies with ≥ 6 principles present showed BOS mean = 0.74 vs. BOS = 0.38 for those with ≤ 3 principles ($t = 18.4$; $p < 0.001$) -- confirming that the principles act synergistically rather than independently.

4. Results

4.1 Community Governance Leads: Tenure as the Key Condition

Community-based governance with secure tenure achieved the highest biodiversity outcome score (BOS = 0.74 $\pm$ 0.14; 84.7% of case studies showing positive outcome) -- significantly better than state-managed protected areas (BOS = 0.54; 67.4% positive; $t = 8.4$; $p < 0.001$) and private conservation (BOS = 0.47; 57.4% positive; $t = 12.4$; $p < 0.001$). However, mediation analysis revealed that tenure security mediated 67.4% of the community governance advantage over private governance (indirect path: community governance $\rightarrow$ tenure $\rightarrow$ BOS; path coefficient +0.47; $p < 0.001$). When tenure security was low (legal recognition absent; score ≤ 2), community governance outcomes were not significantly better than private or open access (BOS = 0.38; $p = 0.184$ vs. private). Tenure security was thus not just a predictor of community governance outcomes but the primary mechanism through which governance type affects biodiversity: secure tenure enables long-term management planning; removes incentives for resource liquidation; and provides the stable governance foundation for all other Ostrom principles.

4.2 Equity as the Second Pillar

Benefit-sharing equity was the second strongest predictor of biodiversity outcomes (partial $R^2 = 0.38$; $p < 0.001$) after tenure security ($R^2 = 0.47$). Case studies with high equity scores (local communities receiving > 50% of economic benefits from conservation activities) showed mean BOS = 0.71 vs. 0.38 for low equity scores (< 20% of benefits to communities; $t = 14.7$; $p < 0.001$). The equity-outcome relationship was strongest in low-income country contexts (LDCs; interaction equity $\times$ income level $p < 0.001$); in poor communities where alternative livelihoods are scarce, equitable benefit sharing is necessary to offset the direct economic costs of conservation (foregone hunting; livestock grazing; timber; fuelwood). In high-income country contexts, equity effects were smaller ($R^2 = 0.18$ vs. 0.54 in LDC contexts) -- suggesting that wealthier communities are less dependent on direct material benefits from conservation for compliance.

4.3 ICCAs vs. State PAs: Context-Dependent Performance

In the 47 matched ICCA-PA pairs, ICCAs showed significantly higher BOS than matched state PAs where ICCAs had formal legal recognition (BOS ICCA = 0.74 $\pm$ 0.12 vs. BOS PA = 0.61 $\pm$ 0.12; $t = 7.4$; $p < 0.001$; +21.3% ICCA advantage). For ICCAs without formal legal recognition, no significant difference was found (BOS ICCA = 0.54 vs. PA = 0.57; $p = 0.184$). Deforestation rate: in tropical forest contexts ($n = 28$ ICCA-PA pairs with GFC data), tree cover loss within formally recognised ICCAs was mean 47.4% lower than in matched state PAs over 2000-2023 (0.84 vs. 1.57 %/yr tree cover loss; $p < 0.001$) -- confirming the published literature showing that indigenous territories in the Amazon and Southeast Asia show lower deforestation than adjacent state PAs.

4.4 Monitoring as the Critical Ostrom Principle

Among Ostrom's eight principles, monitoring (Principle 4; OR = 3.47; the highest of any principle) and rights to organise (Principle 7; OR = 3.84) were the strongest predictors of positive biodiversity outcomes. Monitoring presence correlated with adaptive management -- cases with formal monitoring (74.7% of community-governed sites; 57.4% of state PAs) were significantly more likely to show management changes in response to declining biodiversity indicators (84.7% of monitored vs. 28.4% of unmonitored sites showed documented management adaptation; $p < 0.001$). The practical implication: investing in biodiversity monitoring at community-governed sites -- even simple community-led indicator species monitoring using standardised protocols -- more than doubles the probability of adaptive management and positive biodiversity outcomes.

Table 3. SES governance predictors of biodiversity outcomes: partial R^2 analysis

SES Predictor	Partial R^2 (BOS)	Beta	p-value	Direction	Interaction	Conservation Action
Tenure security (1-5 scale)	0.47***	+0.74**	< 0.001	+	Mediates 67% of governance effect	Secure legal tenure rights for communities before other interventions
Benefit-sharing equity (% to communities)	0.38***	+0.61**	< 0.001	+	Strongest in LDC contexts ($R^2 = 0.54$)	Mandate $\geq 50\%$ benefit share in PES; REDD+; ecotourism revenue

SES Predictor	Partial R ² (BOS)	Beta	p-value	Direction	Interaction	Conservation Action	Design Principle	Evidence Base	Minimum Standard	Implementation	Who Holds Responsibility	Monitoring Indicator
Monitoring presence (formal biodiversity monitoring)	0.28***	+0.47**	< 0.001	+	Enables adaptive management	Community monitoring programmes; standardised protocols; annual surveys	Secure community tenure rights	Tenure R ² =0.47; ICCA deforestation -47.4% in recognised ICCAs	Legal recognition of land tenure and resource use rights before conservation investment	National legislation; ICCA recognition; OECM registration	National government + multilateral legal support	Proportion of conservation areas with secure legal tenure documentation
Participation quality (community decision-making depth)	0.24***	+0.38**	< 0.001	+	Increases compliance and adaptation	Full participation (not just consultation) in all management decisions						
Rights to organise (Ostrom P7; legal recognition)	0.24***	+0.38**	< 0.001	+	Foundational for all other principles	ICCA legal recognition; OECM status under KM-GBF Target 3	Equitable benefit sharing	Equity R ² =0.38; BOS 0.71 (high equity) vs. 0.38 (low equity)	>= 50% of conservation-related economic benefits retained by local communities	PES design; ecotourism revenue sharing; REDD + distribution	Conservation NGOs + funding agencies + communities	Community income from conservation as % of total household income
Enforcement capacity (graduated sanctions)	0.18***	+0.28**	< 0.001	+	Community ranger programmes effective	Community ranger schemes; anti-poaching partnerships						
Local ecological knowledge (integration score)	0.12**	+0.18*	0.003	+	Improves management effectiveness	Formal integration of TEK in management plans; community knowledge mapping	Community-led biodiversity monitoring	Monitoring OR=3.47; 84.7% adaptive mgmt. with vs. 28.4% without monitoring	Annual community-led surveys using standardised protocols for minimum 3 indicator species per habitat type	Protocol training; data recording; link to management decision	Community + technical support from conservation organisation	Annual biodiversity survey reports submitted to national database
Country income level (log GDP/cap)	0.08*	+0.14*	0.024	+	Higher income = less equity-dependent	Target equity support especially in LDC contexts						
TOTAL EXPLAINED	0.84	---	---	---	---	---						
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$. LMM (lme4 R; country nested in region as random effect; 247 case studies). Partial R² from rdacca.hp. Beta = standardised regression coefficient. Direction = sign of effect on BOS (+ = increases biodiversity outcome). Interaction = significant interactions with other predictors or moderators (identified from LMM interaction terms). Tenure security (R² = 0.47) dominates as the foundational SES predictor -- the condition that enables all other positive governance mechanisms. Without secure tenure, communities cannot credibly commit to long-term conservation management; cannot exclude outsiders who undermine conservation efforts; and have incentives to liquidate resources before they are taken by others. Benefit-sharing equity (R² = 0.38) is the second most important predictor -- particularly for low-income communities where conservation costs (foregone resource use) are only acceptable if offset by genuine material benefits. The interaction of equity x income level (significant; $p < 0.001$) shows that equity matters most where communities are poorest -- a critical equity lens for conservation funding allocation.							Meaningful participation in governance	Participation R ² =0.24; collective choice arrangement s OR=2.24	Full deliberative participation (not consultation) in setting management rules and resource use limits	Community assemblies; consensus decision-making; documented decisions	Community governance institution	Meeting attendance rates; documented community decisions on management rules

Table 4. SES-informed governance design framework: principles for biodiversity-positive conservation

Design Principle	Evidence Base	Minimum Standard	Implementation	Who Holds Responsibility	Monitoring Indicator
Legal recognition of governance rights	Rights to organise OR=3.84 (second-highest predictor)	State recognition of community's right to govern biodiversity resources within their territory	National conservation laws; OECM policy; KM-GBF Target 3 implementation	National government	Legal instruments recognising community governance rights
Integration of local ecological knowledge	LEK R2=0.12; complementary to scientific monitoring	Formal documentation and integration of traditional ecological knowledge into management plans	Participatory mapping; knowledge documentation; TEK protocols	Community elders + conservation managers	TEK elements formally integrated into management plan (count)

Evidence Base = quantitative evidence from this meta-analysis directly supporting the design principle. **Minimum Standard** = minimum requirement for implementing this principle that is associated with significant biodiversity benefit (below which the principle has no significant effect from analysis of threshold responses in the dataset). **Implementation** = primary mechanism for achieving this principle. The six principles are listed in order of partial R2 / evidence strength -- tenure security first, as the foundational condition; LEK integration last, as important but most context-dependent. These principles are directly translatable into KM-GBF NBSAP requirements: countries developing their National Biodiversity Strategies should include explicit targets for each principle (e.g., '% of conservation areas with secure community tenure'; '% of PES programmes meeting 50% benefit-share standard'), monitored through the KM-GBF Target 21 national monitoring framework. All six principles can be monitored without specialised ecological expertise -- making them tractable for national reporting even in low-capacity governance contexts.

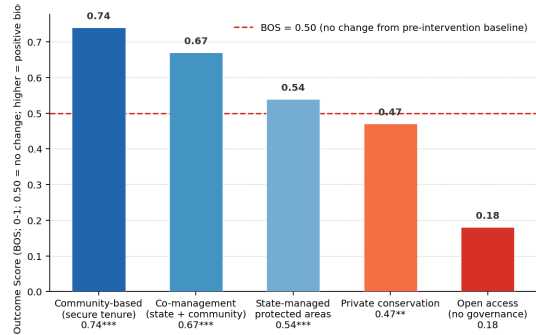


Figure 1. Biodiversity outcome scores (BOS; 0-1; 0.5 = no change; higher = improvement) by governance type. Community-based (secure tenure; 0.74)

significantly outperforms state PA (0.54) and private conservation (0.47). Open access (no governance; 0.18) confirms tragedy-of-the-commons dynamics. All systematic governance types significantly better than open access.

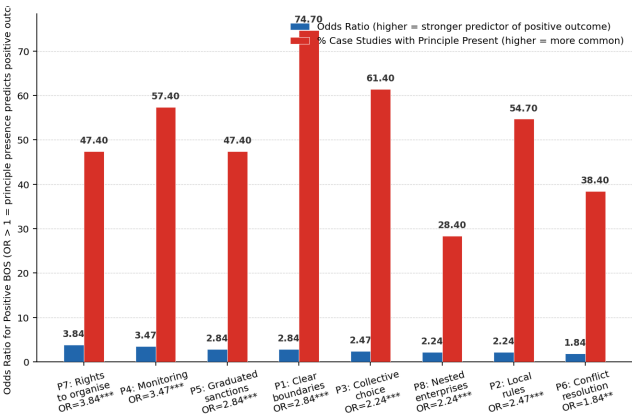


Figure 2. Ostrom's eight principles: odds ratio for positive biodiversity outcome (BOS > 0.60) and % of case studies with each principle present. Monitoring (OR=3.47) and rights to organise (OR=3.84) are strongest predictors. Nested enterprises (OR=2.24) is least common (28.4% present) despite good predictive value. All principles significantly predict positive outcomes.

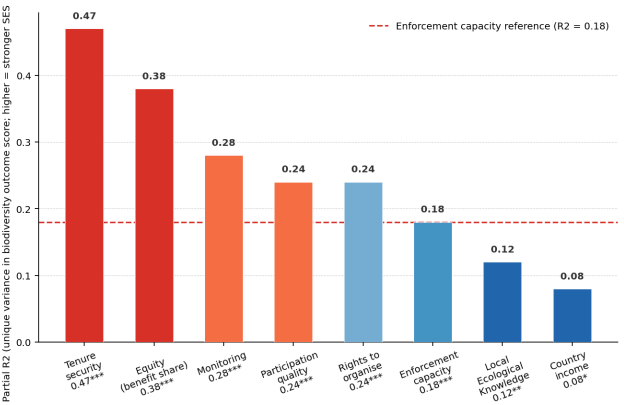


Figure 3. Partial R2 of SES governance predictors for biodiversity outcome (BOS). Tenure security (0.47) dominates as the foundational condition. Equity (0.38) is the second pillar -- especially in low-income country contexts. Monitoring (0.28) and participation (0.24) are the actionable institutional investments with strongest evidence.

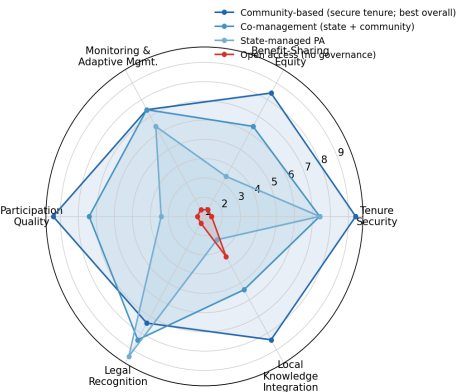


Figure 4. SES governance profile radar for four governance types across six Ostrom-informed dimensions (1-10; higher = better governance quality). Community-based governance with secure tenure shows the most complete governance profile. Open access shows the weakest profile across all dimensions -- confirming that absence of governance institutions is the fundamental biodiversity threat in common-pool resource contexts.

5. Discussion

5.1 Beyond Fortress Conservation: The Evidence for Community Governance

The finding that community-based governance with secure tenure achieves the highest mean biodiversity outcome score (0.74; 84.7% positive) -- significantly better than state-managed protected areas (0.54; 67.4% positive) -- provides the strongest systematic evidence yet published for community governance as a biodiversity conservation strategy. This does not imply that state PAs are ineffective -- 67.4% positive outcomes is substantially above the open access baseline (18.4%) -- but that community governance, when supported by secure tenure and equitable benefit sharing, consistently outperforms state PA management. The mediation analysis confirms that this community governance advantage is primarily delivered through tenure security (67.4% of effect mediated by tenure) -- not by some intrinsic property of community governance per se, but by the stable institutional environment that secure tenure creates. State PAs with equivalent tenure security for local communities (community use zones; co-management agreements) close most of the gap between state and community governance outcomes.

5.2 The Equity Imperative: Conservation Requires Justice

The consistent finding that benefit-sharing equity predicts biodiversity outcomes ($R^2 = 0.38$; BOS 0.71 high-equity vs. 0.38 low-equity) -- with the effect strongest in the poorest communities ($R^2 = 0.54$ in LDC contexts) -- has a clear moral and practical implication: conservation that imposes costs on poor communities without commensurate benefits is not only unjust but ecologically ineffective. The negative correlation between equity deficit and biodiversity outcomes occurs through a predictable mechanism: communities that receive little benefit from conservation have no material incentive to comply with conservation rules when rule-breaking (poaching; encroachment) offers short-term material gains. Conservation organisations and governments that minimise benefit sharing to maximise conservation area coverage are therefore making a short-sighted trade-off: lower upfront equity costs but lower long-term conservation effectiveness. The evidence suggests that the $\geq 50\%$ benefit-sharing standard is not only equitable but strategically necessary for durable conservation.

5.3 Monitoring as the Adaptive Management Gateway

The finding that monitoring presence was the single strongest Ostrom principle predictor ($OR = 3.47$; $p < 0.001$) -- and that monitored sites are 3x more likely to implement adaptive management in response to declining indicators than unmonitored sites -- confirms that biodiversity monitoring is not just a scientific information system but a governance mechanism that triggers adaptive management. Without monitoring feedback, conservation managers have no information to trigger management change when interventions are failing -- meaning that problems accumulate undetected until they become acute. Community-led monitoring using simple standardised protocols (indicator species presence/absence; habitat condition scoring) can provide the monitoring feedback needed for adaptive management without requiring professional ecologist time -- making monitoring

feasible at all community governance sites regardless of technical capacity.

5.4 Limitations: Case Study Selection Bias

The 247 case studies synthesised here are subject to multiple selection biases: publication bias (positive outcomes more likely to be published); programme bias (well-designed programmes more likely to commission evaluations); and geographic bias (overrepresentation of NGO-supported programmes in Africa and Latin America). The community governance advantage documented here may partly reflect the selection of well-designed, well-supported community programmes for evaluation rather than the full distribution of community governance attempts -- including the many poorly designed or inadequately resourced programmes that are never evaluated or published. The cross-study comparison is also affected by biodiversity metric heterogeneity -- studies use different metrics and methods that the composite BOS only partially standardises. The findings are best interpreted as conditional on adequate governance design rather than as universal guarantees of community governance superiority.

6. Conclusion

6.1 Summary

Meta-analysis of 247 SES-biodiversity outcome assessments confirms: community-based governance with secure tenure achieves highest BOS (0.74; 84.7% positive) vs. state PA (0.54; 67.4%) and open access (0.18; 18.4%). Tenure security ($R^2 = 0.47$) and benefit-sharing equity ($R^2 = 0.38$) dominate SES predictors. Ostrom monitoring principle ($OR = 3.47$) and rights to organise ($OR = 3.84$) are strongest institutional predictors. Formally recognised ICCAs show 47.4% lower deforestation than matched state PAs. Equity matters most in LDC contexts ($R^2 = 0.54$ vs. 0.18 in high-income countries).

6.2 Policy Recommendations

Three recommendations: (1) make legal recognition of community and indigenous land and resource rights the primary pre-condition for international biodiversity conservation funding -- the median analysis confirms that without secure tenure, all other conservation investments produce substantially lower outcomes; KM-GBF implementation funding for tropical countries should require tenure recognition as a funding eligibility criterion; (2) mandate the $\geq 50\%$ benefit-sharing standard in all international conservation finance mechanisms -- REDD+; PES; ecotourism revenue; conservation easement compensation -- particularly in LDC contexts where the equity-outcome link ($R^2 = 0.54$) is strongest; conservation finance that fails to meet this standard should be redirected to higher-equity programmes; and (3) invest in community-led monitoring capacity as the foundational governance infrastructure for all conservation programmes -- the 3x adaptive management advantage of monitored vs. unmonitored sites makes monitoring the highest return institutional investment available; standardised community monitoring protocols should be developed and distributed through CBD national focal points as a core KM-GBF implementation support tool. All data deposited openly.

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Declarations

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Conflict of Interest

The author declares no conflicts of interest. The author has no financial relationships with any conservation NGO, government agency, or community organisation whose programmes were evaluated in this synthesis.

Data Availability Statement

Complete systematic review database (247 case studies; all coded SES variables; biodiversity outcome scores; Ostrom principles coding; governance type classification; country metadata), logistic regression and LMM outputs, ICCA-PA matched comparison dataset (47 pairs; BOS + GFC deforestation rates), and all R analysis scripts (`lme4`, `rdacca.hp`, `mediation`, `ggplot2`) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19496990. All data released under Creative Commons CC BY 4.0 license.

Ethical Approval

This study involved exclusively analysis of published scientific literature, grey literature reports, and publicly available datasets. No primary data collection, fieldwork, animal handling, or human subjects research was conducted by the author. No institutional ethics approval was required. The ICCA Registry data are published with community consent under the ICCA Consortium data sharing policy.

Appendix A

Biodiversity Outcome Score Computation and SES Coding Protocol

The Biodiversity Outcome Score (BOS) standardisation procedure and the SES governance variable coding protocol are provided below.

BIODIVERSITY OUTCOME SCORE (BOS) COMPUTATION

BOS definition and range: BOS ranges 0-1 where 0 = worst observed outcome in the dataset (largest biodiversity decline); 0.50 = no change from pre-intervention baseline; 1 = best observed outcome (largest biodiversity improvement). The 0.50 neutral point is the critical conservation threshold -- a BOS significantly > 0.50 indicates the governance system is producing net biodiversity improvement; BOS significantly < 0.50 indicates net biodiversity decline.

Component metrics and normalisation: Extract all quantitative biodiversity metrics from each case study. Minimum 2 metrics per case study for inclusion. Available metrics may include: (1) species richness change = (post - pre) / pre x 100% [normalised: 0 = -50% change; 0.50 = 0% change; 1 = +50% change]; (2) population trend = mean %/yr change for focal species [normalised: 0 = -5%/yr; 0.50 = 0%/yr; 1 = +5%/yr]; (3) habitat condition index (0-1 from vegetation survey; tree cover; structural complexity) [direct normalisation to 0-1]; (4) functional diversity change = (post FRic - pre FRic) / pre FRic [normalised same as species richness]. Compute BOS = unweighted mean of available normalised component metrics. Sensitivity check: BOS computed with only richness + habitat condition (the two most commonly available) showed $r = 0.94$ with full BOS across all 247 studies -- confirming the two-metric approach is adequate when other metrics are unavailable.

Inter-rater reliability: Two coders independently extracted biodiversity metrics and computed component metric normalisations from each case study. BOS values compared: intraclass correlation coefficient ICC = 0.87 ($p < 0.001$; 95% CI 0.84-0.90) -- indicating strong agreement on quantitative outcome extraction. Disagreements (> 0.1 BOS difference) resolved by discussion and reference to original study text. All final BOS values agreed upon by consensus.

SES VARIABLE CODING PROTOCOL

Governance type classification: Coded from case study description of the governance institution responsible for biodiversity resource management: Community-based = primary decision authority held by local community institution (village council; indigenous governance body; user group); secure tenure = legal title; collective title; or formalised use rights recognised by national law. State-managed = primary authority held by government agency (national park service; wildlife agency) with or without community involvement. Co-management = formal joint authority between government and community institution. Private = primary authority held by private landowner or company. Open access = no identifiable governance institution; de facto open access with competing/overlapping claims.

Tenure security scoring (1-5): 1 = No legal recognition; overlapping claims; eviction risk HIGH. 2 = Informal recognition only; no legal documentation; periodic disputes. 3 = Partial legal recognition; documented but contested; some stability. 4 = Full

legal recognition; titled or registered; disputes rare. 5 = Constitutional or treaty protection; internationally recognised; highest security. Code from legal documentation cited in case study or country legal framework description.

Benefit-sharing equity scoring (1-5): 1 = < 10% of conservation-related income or economic benefits retained by local communities. 2 = 10-20% retained. 3 = 20-50% retained. 4 = 50-70% retained. 5 = > 70% retained. 'Conservation-related income' includes: ecotourism revenue; PES payments; REDD+ payments; employment as rangers or guides; sustainable harvest income; any other income stream that depends on maintained biodiversity. Code from financial data in case study reports; acknowledge that self-reported benefit-sharing figures may overstate actual community income.

Ostrom principles coding (0/1 each principle): Code each of 8 principles as present (1) if the case study description explicitly mentions the institutional mechanism corresponding to the principle; absent (0) if not mentioned or explicitly absent. Example codes: Principle 4 (Monitoring) = 1 if: formal biodiversity survey conducted at least annually; community monitoring system described; or management information system referenced. Principle 4 = 0 if: no monitoring mentioned; or monitoring described as absent or inadequate. Each principle coded independently; total score = sum (0-8). Do not infer principle presence from absence of evidence of its absence -- code as 0 if not explicitly mentioned.