

NATURE-POSITIVE RESOURCE GOVERNANCE UNDER CLIMATE AND LAND-USE CHANGE: COUPLED SOCIO-ECOLOGICAL MODELING OF ECOSYSTEM SERVICES, RESOURCE DEPLETION, AND RESILIENCE

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Abstract

Conventional natural resource management paradigms, which treat environmental systems as static and external to economic decision-making, have proven inadequate amid intensifying climate disruption, land-use transformation, and resource depletion. This review synthesizes the conceptual foundations, methodological architectures, and governance innovations underpinning nature-positive resource governance within coupled socio-ecological systems (SES). Drawing on the Kunming-Montreal Global Biodiversity Framework and related policy benchmarks, the paper examines how nature-positive governance transcends incremental sustainability by mandating active ecosystem restoration and regeneration. We critically evaluate modeling paradigms Agent-Based Models, System Dynamics, bioeconomic frameworks, and spatially explicit tools such as InVEST and ARIES comparing their treatment of human agency, spatial-temporal fidelity, and coupling capacity. Particular attention is given to loose, tight, and constitutive coupling paradigms that govern bidirectional feedbacks between social and ecological modules. The review further operationalizes ecosystem services, resource depletion, and resilience through Resource Nexus frameworks (WEF to BEFC), the Ten Pillars of Resilience, Gross Ecosystem Product accounting, and China's Ecological Conservation Redline. Governance architecture is analyzed through polycentric institutions, power dynamics, environmental justice, and relational values, alongside advanced parameter optimization methods including the SalVO framework and policy gradient techniques. Persistent challenges temporal and spatial system mismatches, uncertainty, and validation gaps are addressed through structured evaluation protocols and transdisciplinary co-production. We conclude that integrating high-

performance computation, equity-centered governance, and participatory scenario design is essential for credible, actionable decision-support platforms capable of steering socio-ecological systems toward nature-positive trajectories by 2030 and 2050.

1. INTRODUCTION

Conventional natural resource management approaches have historically operated under paradigms that treat environmental systems as static, infinite, or external to economic decision-making. However, intensifying anthropogenic pressures manifested through climate disruption, sweeping land-use transformation, and unmitigated resource depletion have pushed planetary boundaries to critical thresholds. In response to this compounding planetary crisis, the international policy arena has shifted toward "Nature-Positive" resource governance paradigms (earce & Turner, 1989). Codified in global benchmarks such as the Kunming-Montreal Global Biodiversity Framework (KM-GBF), nature-positive governance moves beyond mere damage mitigation or incremental sustainability; it mandates active restoration and regeneration of ecosystems to halt and reverse biodiversity loss by 2030, charting a long-term trajectory toward living in harmony with nature by 2050 (Colby & Mundial, 1989).

Operationalizing nature-positive targets requires managing key environmental resources such as water, biota, soil, climate, space, and mineral assets alongside derived resources including energy, food, land, and waste. Because the extraction or modification of a single resource reverberates across multiple ecological domains, resource management must navigate complex trade-offs and non-linear system dynamics (Colby, 1990). Transitioning to a nature-positive state demands a fundamental transformation in governance frameworks, replacing fragmented sector-specific management with integrated, adaptive, and polycentric strategies capable of addressing interconnected socio-ecological feedback loops (Neher, 1990).

Defining Coupled Socio-Ecological Systems (SES) and Boundary Specification

Social-Ecological Systems (SES) represent composite human-earth architectures in which social, economic, institutional, and ecological components interact recursively across spatial and temporal scales. Within these tightly coupled architectures, foundational biophysical ecosystem processes generate diverse flows of provisioning, regulating, and cultural ecosystem services (Perella et al., 2026). These service flows directly sustain human well-being and drive socio-economic activities, which in turn inform individual resource-use choices and institutional policy formulations. The resulting governance interventions, extraction regimes, and management rules complete the feedback loop by altering ecosystem structure and biophysical function (Gallopín, 2006).

A foundational challenge in SES research lies in model boundary specification. Delineating system boundaries requires balancing conceptual realism against computational and analytical tractability. Arbitrarily restrictive boundaries risk omitting critical cross-scale linkages such as telecoupling, regional hydrological flows, or macro-economic market drivers thereby leading to policy resistance or unexpected system failures (Bruckmeier, 2016). Conversely, overextending boundaries increases model complexity, parameter uncertainty, and data requirements, often rendering models inscrutable or computationally inefficient. Establishing robust boundary frameworks requires explicit criteria that capture primary socio-ecological feedbacks while aligning spatial and temporal scales with the operational governance mechanisms under study (Filatova & Polhill, 2012).

Complex Adaptive Dynamics, Non-linearity, and Tipping Points

Social-ecological systems operate as complex adaptive systems characterized by non-linear

responses, historical path dependencies, heterogeneous micro-level interactions, and emergent macro-level behaviors. Unlike linear environmental systems, SES exhibit tipping points thresholds beyond which small incremental perturbations in drivers like climate or land-use change trigger sudden, catastrophic shifts in ecosystem state and service delivery (de Souza Sant'Anna, 2006).

Static or equilibrium-centric modeling approaches, such as classic bioeconomic models, often fail to capture these non-linear dynamics because they assume smooth, continuous

regeneration functions and predictable human optimization behaviors (Iancu & Lanteigne, 2022). Under severe environmental stress, non-linear feedbacks between resource depletion and human coping strategies can amplify vulnerability, accelerating degradation. Modeling nature-positive governance requires frameworks capable of simulating non-equilibrium dynamics, structural adaptive responses, and regime shifts across heterogeneous landscapes (Scheffran et al., 2025).

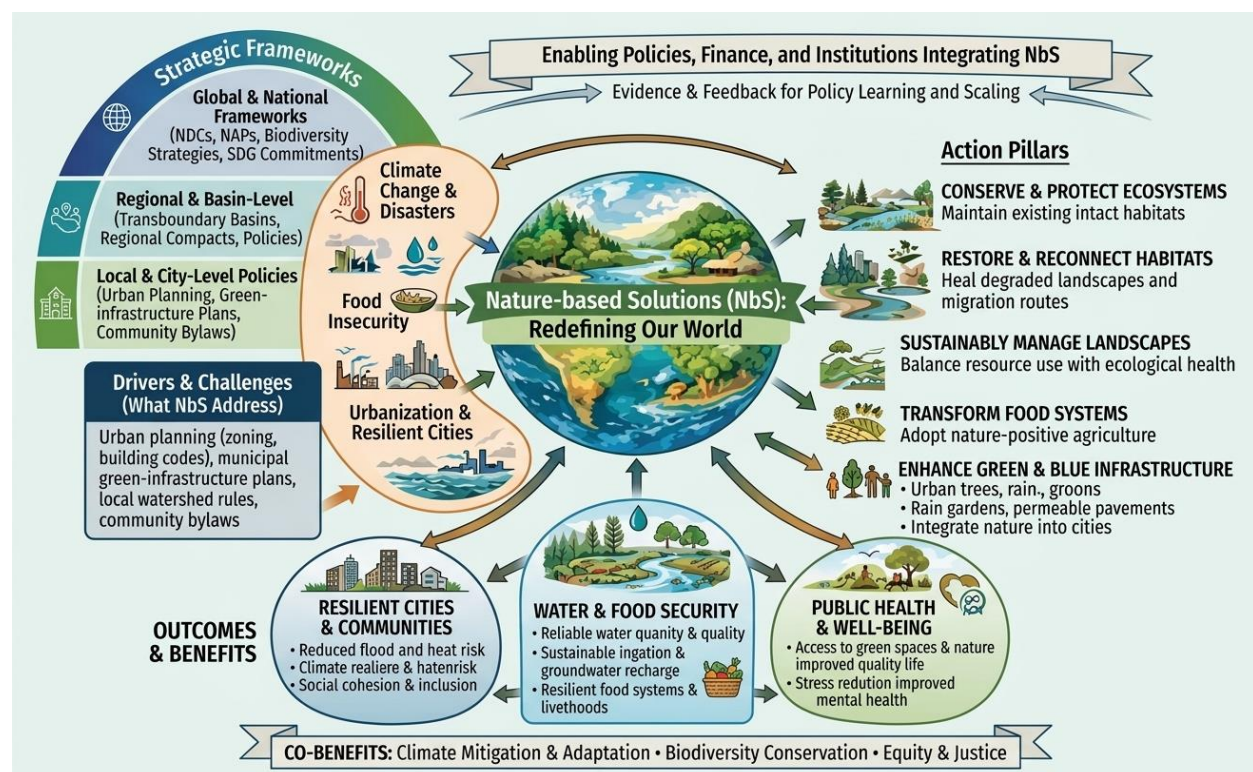


Figure 1: Multilevel Governance, Drivers, and Action Pillars of Nature-Based Solutions (NbS) for Socio-Ecological Co-Benefits.

2. Methodological Architecture of Coupled Socio-Ecological Modeling

2.1 Agent-Based Models, System Dynamics, and Bioeconomic Frameworks

A diverse set of modeling methodologies has been developed to capture the dynamic couplings between human decision-making and environmental processes. Agent-Based Models (ABM) simulate systems as collections of

autonomous, heterogeneous entities (e.g., individual land managers, households, regulatory bodies) that interact with each other and their spatial environment according to specified behavioral rules (Breier et al., 2026). ABMs excel at capturing emergent macro-level phenomena such as collective resource management or structural land-use change from micro-level behavioral interactions. However, parameterizing

human decision-making and validating high-dimensional agent configurations remain major challenges (Belem & Saqalli, 2017).

System Dynamics (SD) modeling conceptualizes SES through continuous stock-and-flow structures governed by interconnected feedback loops and differential equations. SD is effective for analyzing aggregated systemic dynamics, lag effects, and policy levers over multi-decadal time horizons. Yet, traditional SD models often lack spatially explicit boundaries and struggle to represent fine-grained spatial heterogeneity or individual decision diversity (Ziv et al., 2020).

Bioeconomic models combine economic optimization principles with biological growth and regeneration functions. While bioeconomic models historically evaluated steady-state yields and optimal resource extraction rents (notably in exhaustible resources or marine fisheries), their application to complex terrestrial social-ecological systems has declined due to their reliance on overly simplistic human utility functions and linear environmental dynamics (Nugroho & Uehara, 2023).

2.2 Spatially Explicit Ecosystem Service Modeling Tools

Spatially explicit tools translate changes in land use, land cover, and climate into quantifiable shifts in ecosystem service provision. Prominent among these is the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) framework, which utilizes deterministic, biophysical production functions to map and value ecosystem services such as carbon storage, water yield, sediment retention, and habitat quality across geographic grids. InVEST is widely favored for its standardized structure, spatial resolution, and policy accessibility, though it relies largely on static equilibrium assumptions (Ochoa & Urbina-Cardona, 2017).

Alternative platforms, such as Artificial Intelligence for Ecosystem Services (ARIES), utilize Bayesian Belief Networks (BBNs) and agentic semantic web algorithms for dynamic mapping of service flows from supply regions to human beneficiaries (Bagstad et al., 2013).

Furthermore, non-monetary valuation tools like SoLVES (Social Values for Ecosystem Services) capture social and relational values across landscapes. To simulate future spatial patterns, ecosystem service models are frequently integrated with land-use change models such as Cellular Automata (CA) and the Future Land-Use Simulation (FLUS) model, enabling land transition projections under explicit zoning constraints (Bühns et al., 2026).

2.3 Coupling Paradigms: Loose, Tight, and Constitutive Integration

Coupling distinct disciplinary models such as joining an ecological growth model with a socio-economic agent model presents fundamental computational and architectural choices. The degree of coupling directly dictates model maintainability, computational speed, and the ability to capture dynamic feedbacks (Keyes et al., 2013).

Loose coupling involves integrating separate software components through standardized external file exchanges, offline data pipelines, or asynchronous web service interfaces (e.g., Service-Oriented Architecture - SOA). In a loosely coupled system, models run sequentially: output files from an ecological model serve as inputs for a socio-economic model without altering internal execution logic. While this modularity simplifies code maintenance and accommodates multi-language development, it restricts real-time dynamic feedback loops, making it difficult to capture rapid socio-ecological adaptations occurring within single time steps (Guo et al., 2026).

Tight coupling integrates disciplinary modules within a unified computational memory space or through direct interface wrappers. Programs dynamically exchange variable states at high frequency during run-time execution loops. Advanced modular modeling frameworks such as copan:LPJmL, which connects the copan:CORE human-earth system platform to the LPJmL dynamic global vegetation model via Python wrappers (pycoupler) exemplify tight coupling. Tight coupling enables bidirectional feedback

loops across spatial grids and time steps, though it demands rigorous alignment of spatial-temporal scales and increases software development complexity (León et al., 2019). Constitutive coupling represents an emerging paradigm in digital twin and agentic SES modeling. In constitutive coupling, the digital

representation and the physical governance system mutually define and alter one another's identity. The unit of analysis shifts to a hybrid, co-evolving system where model updates, real-time sensing, and human governance decisions continually reconfigure the system's operational parameters and boundaries (Orton & Weick, 1990).

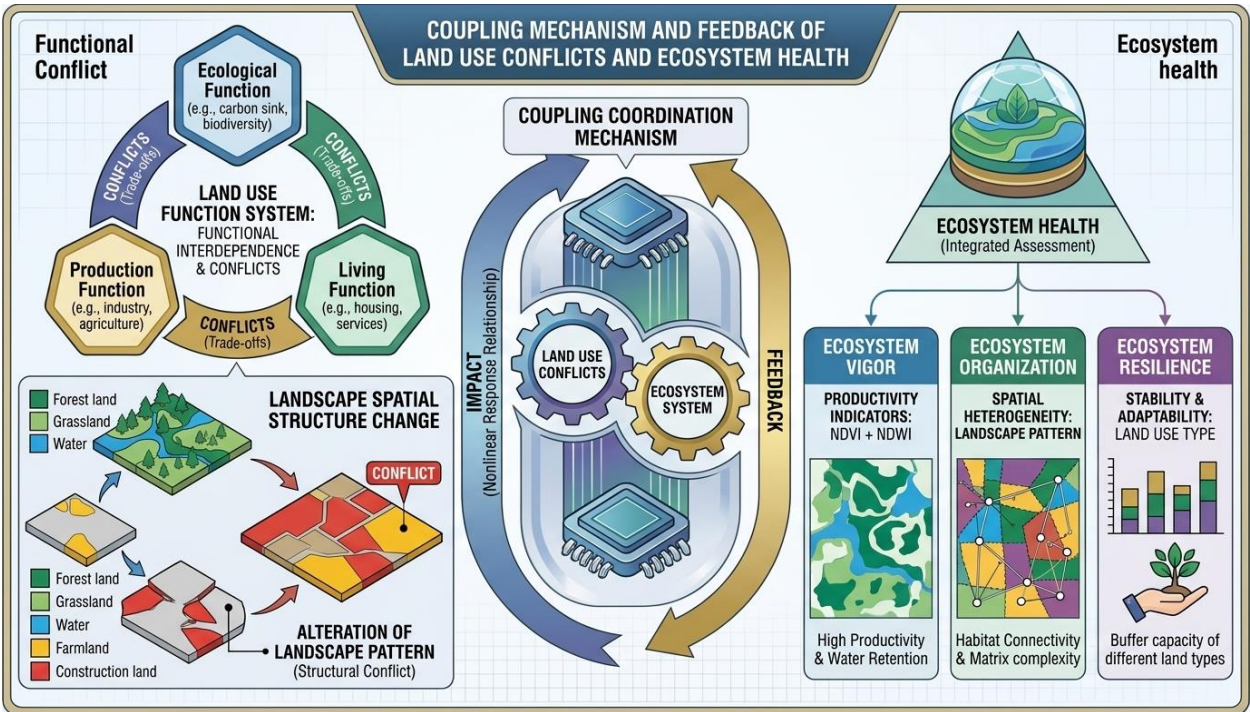


Figure 2: Coupling Coordination Mechanism and Dynamic Feedback Loops Linking Land Use Conflicts with Ecosystem Health Indicators.

Table 1: Comparative Analysis of Modeling Paradigms for Socio-Ecological Systems

Modeling Paradigm	Primary Mathematical / Computational Base	Spatial & Temporal Fidelity	Representation of Human Agency	Coupling Capacity & Methods	Key Strengths & Operational Bottlenecks
Agent-Based Modeling (ABM) [cite: 9, 11, 12, 13]	Object-oriented programming, rule-based algorithms, state transitions	High spatial resolution (micro-grid/agent level); discrete temporal steps	High: explicit representation of individual heterogeneity, social networks, and adaptive behaviors	High: can be tightly coupled with ecological models via shared memory or wrappers	Strengths: Captures emergent macro-phenomena and institutional dynamics.

Bottlenecks: High computational cost, complex parameterization, difficult validation. | | **System Dynamics (SD)** | Continuous differential and difference equations, stock-and-flow logic | Low-to-moderate spatially explicit resolution; continuous temporal domains | Moderate: aggregated policy loops, structural rules, and non-linear feedback loops | Moderate: typically loosely coupled to spatial GIS layers or external models | **Strengths:** Excellent for macro-level systemic feedback and multi-decadal policy analysis (Binder et al., 2013).

Bottlenecks: Lacks spatial heterogeneity and individual decision diversity. | | **Spatially Explicit Tools (InVEST / ARIES)** | Biophysical algorithms, spatial matrices, Bayesian Belief Networks | Very high spatial resolution (raster/vector grids); static or coarse temporal steps | Low: human actors treated primarily as passive drivers (land-use classes) or static beneficiaries | High: frequently coupled loosely or tightly with CA-FLUS or ABM land-use drivers | **Strengths:** Robust spatial visualization and standardized biophysical valuation of ecosystem services (Schlüter et al., 2019).

Bottlenecks: Limited internal temporal dynamics and social adaptive feedbacks. | | **Bioeconomic Optimization** | Dynamic programming, calculus of variations, steady-state bioeconomic equations | Low spatially explicit resolution; dynamic temporal optimization | Moderate: single idealized rational agent maximizing net present economic value | Low: rigid mathematical formulation limits external computational coupling | **Strengths:** Analytical clarity regarding optimal resource extraction rents (Glendell et al., 2025).

Bottlenecks: Unrealistic assumptions of system linearity, perfect information, and homogeneous behavior. | | **Integrated Hybrid Frameworks (e.g., copan:LPJmL, SalVO)** | High-performance compiled code, vectorized linear algebra, deep coupling wrappers | High spatial (global/regional grid) and high dynamic temporal resolution |

High: integrates differentiable socio-economic agents with global biophysical process models | Advanced: tight to constitutive coupling via dynamic interface libraries and memory sharing | **Strengths:** Captures full bidirectional human-Earth system feedbacks across scales (Nugroho & Uehara, 2023).

Bottlenecks: Extreme computational overhead; requires interdisciplinary software architecture (Rounsevell et al., 2021). |

3. Operationalizing Ecosystem Services, Resource Depletion, and Resilience

3.1 Resource Nexus Paradigms: From WEF to BEFC Frameworks

Resource management strategies increasingly leverage "Resource Nexus" frameworks to address the interdependencies inherent in socio-ecological systems. The early conceptual literature focused primarily on the Water-Energy-Food (WEF) Nexus, examining trade-offs between agricultural production, energy generation, and freshwater allocation. As climate impacts intensified, the framework expanded into the Water-Energy-Food-Climate (WEFC) Nexus (Sambo et al., 2024).

Recent nature-positive governance frameworks advocate for the Biota-Energy-Food-Climate (BEFC) Nexus, which elevates biological diversity and ecosystem integrity to core structural components rather than peripheral externalities. Within this structural hierarchy, foundational key environmental resources (including water, biota, soil, materials, climate, and space) undergo biophysical transformations to generate derived environmental resources (such as food, energy, converted land, maritime products, and waste streams) (Vrachioli et al., 2025). Socio-economic drivers and feedback mechanisms influence the extraction and conversion of these derived resources, requiring targeted nature-positive governance levers to manage cross-sectoral trade-offs. Adhering to the principle of parsimony (Occam's razor), coupled models operationalize the Resource Nexus by using the smallest viable set of interacting system state variables required to

represent cross-resource trade-offs (David et al., 2024).

3.2 Quantitative Evaluation Frameworks: Ten Pillars of Resilience and Gross Ecosystem Product

Evaluating socio-ecological outcomes under climate and land-use change requires standardized, multidimensional monitoring frameworks. To bridge the gap between theoretical resilience concepts and actionable policy metrics, operational frameworks such as the Ten Pillars of Resilience (TPOR) have been established (Joshi et al., 2023). TPOR organizes system metrics across a three-tiered structural hierarchy:

- 1. **Pillars:** Primary constituents of resilient social-ecological systems across expansive landscapes.
- 2. **Elements:** Core structural features and functional processes within each Pillar.
- 3. **Metrics:** Quantitative spatial, physical, socio-economic, and biological indicators used to assess performance over time (Lewandowski et al., 2024).

In parallel, economic accounting has evolved through the establishment of Gross Ecosystem Product (GEP). GEP quantifies the aggregate monetary value of final ecosystem services delivered to human society within a defined region over a given period (O’Connell et al., 2015). Mathematically, GEP synthesizes functional provisioning, regulating, and cultural ecosystem services:

GEP = \sum_{i=1}^m E_{p,i} \cdot P_{p,i} + \sum_{j=1}^n E_{r,j} \cdot P_{r,j} + \sum_{k=1}^l E_{c,k} \cdot P_{c,k}

where E_p, E_r, E_c represent the physical quantities of provisioning, regulating, and cultural services provided, and P_p, P_r, P_c represent their respective explicit or surrogate market prices. Integrating GEP into national accounting complements traditional Gross Domestic Product (GDP), preventing the mischaracterization of ecosystem asset depletion as pure economic growth (Talampas et al., 2025).

3.3 Spatial Policy Tools and Zoning: The Ecological Conservation Redline

To operationalize nature-positive targets, spatial governance frameworks deploy targeted land-use zoning policies. China’s Ecological Conservation Redline (ECR) framework serves as a prominent spatial policy mechanism. ECR delineates key ecological regions characterized by high ecosystem service value, critical habitat needs, or severe ecological fragility and places them under strict statutory protection where development is restricted (Guo et al., 2023).

Integrating ECR constraints into spatial coupled models (e.g., CA-FLUS coupled with InVEST) allows researchers to simulate land-use transitions under explicit ecological safeguards. Empirical assessments demonstrate that strictly enforced spatial boundaries mitigate ecological fragmentation, stabilize regional carbon sinks, and enhance soil and sediment retention under changing climate projections (Lü et al., 2013).

Table 2: Key Indicators and Operational Constructs for Nature-Positive Governance Evaluation

Policy / Analytical Construct	Governance Dimension	Primary Metrics & Indicators	Spatial / Temporal Domain	Representative Framework / Application
Kunming-Montreal Global Biodiversity Framework (KM-GBF)	International targets; net-positive biodiversity governance	Target 3: 30% spatial protection of lands and oceans; Target 14: Integration of biodiversity across sectors; Target 19:	Global to national; targeted milestones for 2030 and 2050	Global environmental policy implementation and National Biodiversity Strategies and

		Resource mobilization		Action Plans (NBSAPs)
Ten Pillars of Resilience (TPOR)	Landscape resilience evaluation and operational monitoring	Hierarchical pillars, elements, and quantitative metrics assessing socio-ecological health, forest structure, and recovery potential	Landscape to regional scale; multi-temporal monitoring	Forest landscape restoration, wildland fire management, and climate adaptation investments
Gross Ecosystem Product (GEP)	Economic valuation; ecological asset accounting	Monetized sum of provisioning (food, water), regulating (carbon sequestration, flood control), and cultural services (<i>GEP</i>)	Sub-national, municipal, and regional accounting units; annual evaluation	Regional ecological compensation, eco-civilization planning, and green national accounting
Ecological Conservation Redline (ECR)	Spatial zoning and regulatory land-use control	Area coverage of designated redline zones; Ecosystem Service Landscape Index; habitat suitability metrics	High spatial resolution (grid/cell level); long-term land-use planning horizons	Spatial planning, protection of key ecological function zones, and biodiversity hotspots
Biota-Energy-Food-Climate (BEFC) Resource Nexus	Inter-sectoral resource trade-off optimization	Primary resource consumption rates; cross-sectoral trade-off indices; eco-efficiency and resource loss rates	Regional, basin-wide, or national scope; continuous/stepwise simulation	Integrated natural resource management, climate adaptation, and sustainable development planning

4. Decision-Making, Governance Architecture, and Human Agency

4.1 Multi-Level, Polycentric Governance and Institutional Dynamics in ABMs

The representation of governance within coupled socio-ecological models has historically suffered from oversimplification. Early agent-based models frequently treated governance as static, top-down external forcing functions or assigned agents overly simplistic utility-maximizing behaviors. Recent modeling advances emphasize multi-level, polycentric governance structures characterized by multiple overlapping decision-making centers with autonomous authority (Zeng et al., 2025).

Polycentric governance operates through a dynamic feedback loop between formal

institutions (e.g., statutory laws, extraction quotas) and informal institutions (e.g., customary norms, social trust). These institutional rule sets shape the decision-making matrices of boundedly rational agents, whose resource extraction actions alter ecological stock dynamics (Kianpour et al., 2022). In response to emerging ecological stressors, resource depletion, or tipping point risks, actors engage in adaptive monitoring and rule reconfiguration, transforming the overarching governance architecture over time. Applying Ostrom's Institutional Analysis and Development (IAD) framework within ABMs allows agents to adjust their decision rules based on institutional feedback, monitoring, and sanctioning mechanisms (Mathias et al., 2017).

4.2 Incorporating Power Dynamics, Relational Values, and Environmental Justice

A critical gap in coupled hydrological and ecological modeling is the omission of power asymmetries, environmental justice (EJ), and relational values. Traditional water management and resource models often project an aura of technical neutrality, concealing how model assumptions enforce dominant socio-political agendas or marginalize vulnerable communities. Governance and resource access are shaped by political power, economic status, and institutional authority (Rodríguez & Inturias, 2018).

Integrating power dynamics into coupled SES models requires configuring agent access to resource rents, political influence, and decision-making bodies as heterogeneous variables. Furthermore, incorporating relational values defined as the cultural, ethical, and identity-driven connections between human communities and specific landscapes moves beyond monetary utility frameworks. Tightly or loosely coupling environmental justice objectives into governance algorithms ensures that model scenarios evaluate equity, distributional justice, and historical pollution burdens alongside economic efficiency and ecological conservation targets (Schlosberg et al., 2026).

4.3 Advanced Parameter Optimization and High-Performance Calibration

Parameterizing complex social-ecological ABMs with thousands of heterogeneous, interacting agents presents significant computational bottlenecks. Standard calibration techniques, such as Simulated Minimum Distance or brute-force Monte Carlo sweeps, fail to scale past a small number of parameters (Li et al., 2026). Recent innovations in high-performance simulation architectures exemplified by the SalVO framework and the VDSK-B model (linking macro-economics, climate dynamics, and ecological assets) overcome these limitations by expressing agent state updates as recursive, vectorized functions (Robin et al., 2021).

SalVO leverages hardware acceleration and specialized optimization algorithms to calibrate

high-dimensional, stochastic agent-based models. For deterministic, differentiable ABM modules, automatic differentiation via backpropagation enables gradient-based optimization across thousands of policy parameters. For stochastic, non-differentiable agent interactions, SalVO introduces the GP-ABM protocol using policy gradient methods (such as Williams' REINFORCE algorithm) (Bennet & Selvakani, 2025). The policy gradient formulation computes parameter updates by maximizing expected reward functions over simulated agent trajectories τ :

$$\nabla_{\theta} J(\theta) = \mathbb{E}_{\tau \sim \pi_{\theta}} \left[\sum_{t=0}^T \nabla_{\theta} \log \pi_{\theta}(a_t | s_t) R(\tau) \right]$$

where θ represents model parameters, $\pi_{\theta}(a_t | s_t)$ is the agent action probability given state s_t , and $R(\tau)$ is the cumulative socio-ecological outcome score. These methods allow large-scale policy optimization in planetary-scale socio-ecological models, executing simulations faster than traditional unvectorized platforms (Wei et al., 2019).

5. Challenges, Emerging Horizons, and Policy Synthesis

5.1 System Mismatches, Uncertainty, and Model Validation

Modeling coupled socio-ecological dynamics entails addressing fundamental spatial, temporal, and conceptual system mismatches. Temporal mismatches occur because human decision-making cycles operate on rapid time scales (e.g., daily market trades, seasonal agricultural choices, annual budget cycles), whereas biophysical processes unfold over multi-decadal or centennial scales (e.g., soil formation, forest succession, deep groundwater recharge) (Da et al., 2025). Spatial mismatches arise when administrative boundaries (e.g., municipal or national borders) conflict with natural ecological units (e.g., watersheds or migratory corridors) (Hinov, 2026).

Addressing these mismatches requires robust verification and validation protocols. Model evaluation platforms such as the TRACE (Transparent and Comprehensive Model Evaluation) framework provide structured protocols for documenting model purpose,

parameterization rationale, software verification, and sensitivity testing. Systematic application of TRACE ensures that complex SES models are transparent, reproducible, and sufficiently credible to support real-world natural resource governance decisions (Kiasari & Aly, 2026).

5.2 Bridging the Science-Policy-Practice Divide via Transdisciplinary Co-Production

A central bottleneck in socio-ecological modeling is the science-policy-practice gap, wherein scientific models remain disconnected from real-world decision-making processes. Bridging this divide requires transitioning from traditional top-down, expert-driven modeling toward transdisciplinary co-production. Transdisciplinary methodologies integrate local ecological knowledge, citizen science, and stakeholder perspectives directly into model conceptualization, boundary definition, and scenario design (Adelle et al., 2020).

In a transdisciplinary co-production workflow, scientific researchers, local knowledge holders, and policy actors collaboratively establish system boundaries and design exploratory scenarios. Stakeholders interact directly with coupled simulation engines through participatory tools, serious gaming, and 3D spatial visualizations to evaluate policy options (Leith et al., 2017). The resulting model outputs inform adaptive policy formulation, ensuring that governance decisions reflect institutional realities, relational values, and equity concerns. Closing the science-policy-practice cycle transforms quantitative models into shared decision-support platforms for nature-positive resource governance (Bhandari et al., 2026).

Conclusion

This review demonstrates that achieving nature-positive resource governance under compounding climate and land-use change demands a fundamental reorientation of both analytical frameworks and institutional architectures. Conventional equilibrium-centric and sector-fragmented approaches are structurally incapable of capturing the non-linear feedbacks, tipping points, and cross-scale telecouplings that characterize coupled socio-ecological systems. The

methodological landscape has consequently matured toward hybrid, spatially explicit, and tightly coupled frameworks exemplified by copan:LPJmL and SalVO that integrate heterogeneous human agency with dynamic biophysical processes. Yet, technological sophistication alone is insufficient. Operationalizing nature-positive targets requires standardized multidimensional metrics, including the Ten Pillars of Resilience, Gross Ecosystem Product, and the Biota-Energy-Food-Climate Nexus, which together reframe ecological integrity as a structural precondition rather than an externality. Equally critical is the explicit incorporation of power asymmetries, environmental justice, and relational values into governance algorithms, ensuring that modeled scenarios evaluate equity alongside efficiency. Persistent challenges of temporal-spatial mismatch, parameter uncertainty, and validation demand rigorous protocols such as TRACE. Ultimately, closing the science-policy-practice divide through transdisciplinary co-production where stakeholders, local knowledge holders, and researchers jointly define boundaries and scenarios transforms quantitative models into legitimate, shared decision-support platforms. Realizing the 2030 and 2050 biodiversity and harmony-with-nature targets will depend on this convergence of computational innovation, polycentric institutional design, and participatory governance.

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