

# Multi-Agent Dynamic Resource-Allocation and Cooperation Problem: AI-Supported Market Public-Goods Simulation

## Abstract

Coordinating investment in shared natural resources presents a fundamental public goods challenge: benefits are collective but costs are distributed unevenly across stakeholders. This proposal develops a probabilistic multi-agent simulation framework using NumPyro to model cooperation dynamics between interdependent actors in watershed management. We focus on the real-world case of erosion mitigation through upstream reforestation that benefits downstream hydropower infrastructure. **We have developed a working prototype demonstrating the core methodology**, which enables counterfactual analysis of different cooperation mechanisms (cost-sharing, performance-based contracts, carbon credit trading) to identify incentive structures that align private payoffs with collective ecological outcomes. Deliverables include an open-source simulation toolkit, interactive dashboard for scenario exploration, and integration with hypercerts for transparent impact verification.

## Problem Statement

### The Watershed Cooperation Challenge

A hydropower dam downstream faces increasing sediment inflow caused by degradation of an upstream hillside forest. The forest and dam belong to different owners, yet their outcomes are tightly linked: reforesting the slope would reduce erosion, protect reservoir capacity, and generate ecosystem co-benefits including carbon sequestration and slope stability. Because these benefits are shared but unevenly distributed, actors must coordinate financing, maintenance, and monitoring of restoration efforts over time.

This scenario exemplifies the **multi-agent public goods problem**: each actor has private incentives that may conflict with collectively optimal outcomes. The challenge is designing incentive-compatible rules that align individual payoffs with ecological goals while ensuring distributional fairness.

### The Agents

| Agent                 | Role                   | Incentive Structure                                    |
|-----------------------|------------------------|--|
| Dam Owner/Operator    | Downstream beneficiary | Reduce sediment inflow, maintain hydropower efficiency |
| Forest Owner          | Land steward           | Credit revenues, land value appreciation               |
| Ecological Expert/NGO | Verifier               | Scientific integrity, ecological outcomes              |
| Government/Regulator  | Public interest        | Infrastructure protection, climate resilience          |
| Private Investor      | Capital provider       | ROI on carbon credits, ESG alignment                   |

# Technical Approach

## Probabilistic Multi-Agent Framework

We develop a unified Bayesian framework in **NumPyro** integrating three modeling layers:

- 1. Ecological Dynamics:** Forest health evolves via stochastic logistic growth; erosion decays exponentially with forest cover. This captures the key physical mechanism linking upstream restoration to downstream benefits.
- 2. Hierarchical Agent Decisions:** Agents contribute based on mechanism incentives, individual cooperation tendencies (drawn from a shared distribution), and ecological urgency. The hierarchical structure enables partial pooling—learning about agent heterogeneity while borrowing strength across types.
- 3. Mechanism Comparison:** Using NumPyro's **do** operator for causal intervention, we evaluate counterfactual outcomes under different cooperation rules, computing Average Treatment Effects (ATEs) with full uncertainty quantification.

## Key Innovation

Our approach uniquely combines:

- **Bayesian uncertainty quantification** for robust decision-making
- **Causal inference tools** (**do** operator) for counterfactual mechanism comparison
- **Hierarchical structure** capturing heterogeneous agent behaviors

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## Proof of Concept: Preliminary Results

We have developed a **working prototype** demonstrating the full methodology. Key findings from initial simulations (500 Monte Carlo samples, 20-year horizon):

### Understanding the Three Cooperation Mechanisms

Each mechanism represents a different way to structure financial incentives and risk-sharing among stakeholders:

#### 1. Cost-Sharing (Baseline)

**How it works:** All agents contribute a fixed proportion of restoration costs regardless of outcomes. The dam owner pays X%, the forest owner pays Y%, and the government/investors cover the remainder. Contributions are predetermined and predictable.

**In the model:** Agent contributions scale linearly with a baseline rate (60%) plus individual cooperation tendencies. The incentive modifier is neutral (1.0×).

**Why the outcomes:** Cost-sharing provides *stable but modest* results because:

- Agents have no direct incentive to maximize ecological outcomes—they pay the same whether the forest thrives or fails

- Free-rider problems persist: agents may contribute minimally since their payment is fixed
- Risk is distributed but so is responsibility, diluting accountability

**Result:** Mean forest health of 0.58 and erosion of 0.52 tons/yr—adequate but not optimal.

## 2. Performance-Based Contracts

**How it works:** Payments are tied to verified ecological milestones. The forest owner receives larger payments only when measurable targets are achieved (e.g., forest health > 0.7, erosion reduction > 30%). The dam owner pays more for delivered results rather than promised efforts.

**In the model:** The incentive modifier increases to 1.3x when forest health is degraded (< 0.5), creating urgency. Agent contributions become outcome-contingent rather than fixed.

**Why the outcomes:** Performance contracts produce *consistently strong* results because:

- Direct link between payment and outcomes aligns private incentives with public goods
- Ecological urgency triggers increased investment when most needed
- The forest owner has clear financial motivation to achieve targets
- The dam owner gets assurance that payments translate to actual erosion reduction

**Result:** Mean forest health of 0.86 and erosion of 0.41 tons/yr—substantial improvement over baseline.

## 3. Carbon Credit Trading

**How it works:** Reforestation generates verified carbon credits (e.g., VCS or Gold Standard certified). These credits can be sold on carbon markets, attracting private investors/corporates seeking ESG compliance. The carbon price creates an external revenue stream that supplements stakeholder contributions.

**In the model:** The incentive modifier is highest (1.5x) but contributions have increased variance, reflecting market price volatility and speculative dynamics.

**Why the outcomes:** Credit trading achieves *highest performance with higher uncertainty* because:

- External capital injection (carbon buyers) significantly increases total investment
- Market-based mechanism efficiently allocates resources to highest-impact activities
- However, carbon prices are volatile—strong performance in bull markets, potential underfunding in downturns
- Speculative behavior introduces variance: investors may over- or under-commit based on market sentiment

**Result:** Mean forest health of 0.92 and erosion of 0.38 tons/yr—best average outcomes but with wider confidence intervals.

### Mechanism Comparison Results (Summary)

| Mechanism    | Mean Forest Health | Mean Erosion | Interpretation                                      |
|--------------|--------------------|--------------|---|
| Cost-Sharing | 0.58               | 0.52 tons/yr | Predictable but modest; no incentive for excellence |

| Mechanism            | Mean Forest Health | Mean Erosion | Interpretation  |
|----------------------|--------------------|--------------|---|
| Performance Contract | 0.86               | 0.41 tons/yr | <b>Strong ecological outcomes;</b> clear accountability |
| Credit Trading       | 0.92               | 0.38 tons/yr | Highest mean performance; market-dependent variance     |

Reading the metrics:

- *Forest Health*: Scale 0–1, where 1.0 = fully restored forest canopy with maximum erosion control
- *Erosion*: Annual sediment load entering reservoir; lower = better dam protection

Counterfactual Analysis: Quantifying the Policy Decision

Using NumPyro's `do` operator for causal intervention, we answer the critical policy question: *"What would happen if we switched from one mechanism to another?"* This goes beyond correlation to estimate causal effects.

| Policy Switch                       | Forest Health $\Delta$ | Erosion $\Delta$ | Practical Meaning                                   |
|-------------------------------------|------------------------|------------------|---|
| Cost-Sharing → Performance Contract | <b>+0.28</b>           | <b>-0.11</b>     | Forest health improves by 48%; erosion drops by 21% |
| Cost-Sharing → Credit Trading       | <b>+0.34</b>           | <b>-0.14</b>     | Forest health improves by 59%; erosion drops by 27% |

*Positive Forest Health  $\Delta$  = improvement; Negative Erosion  $\Delta$  = improvement*

**What this means for policymakers:** Moving from the default cost-sharing arrangement to performance-based contracts would deliver nearly half again as much forest restoration with predictable outcomes. Carbon trading could achieve even more but requires tolerance for market-driven uncertainty.

Key Insights

1. **Performance-based contracts consistently outperform cost-sharing** because they directly incentivize ecological results rather than just participation
2. **Credit trading attracts more capital** but introduces outcome variance—suitable when markets are stable and stakeholders can absorb volatility
3. **No mechanism dominates on all criteria**—optimal choice depends on stakeholder risk tolerance, regulatory environment, and available market infrastructure
4. **The framework enables quantified trade-off analysis** that traditional approaches cannot provide—policymakers can see not just "which is better" but "by how much, with what confidence"

References

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*Grant application for AI4PG 2025: <https://www.recerts.org/ai4pg2025>*