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A systems thinking approach to improve participatory processes in small-scale fisheries management

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Abstract

Systems thinking offers a powerful way to address complex social–ecological challenges, yet many approaches remain difficult to implement in data-poor, participatory management settings. We developed and applied a practical decision-support framework that integrates participatory causal loop diagramming, stochastic token diffusion modeling, and network centrality analysis. We applied the framework to small-scale octopus (*Octopus mimus*) fisheries in Peru and Chile, where sustainability is challenged by data limitations, informal harvesting, market pressures, and compliance. Through a series of participatory workshops, stakeholders co-developed causal maps, identified shared sustainability goals, evaluated potential interventions, and interpreted network-based analyses. Across both fisheries, stakeholders converged on octopus abundance and fisher compliance as the primary sustainability goals. Token diffusion simulations indicated that traceability interventions produced the strongest and most rapid improvements in fisher compliance, whereas octopus abundance responded through multiple intervention pathways. Network centrality analyses identified several practical monitoring candidates, including landing price, fishing effort, total landings, debt, fishers' concern for sustainability, and processing quality. The analyses also revealed country-specific dynamics, including stronger propagation of intervention effects in Chile and distinct leverage points associated with product stockpiling. Our findings demonstrate how integrating participatory systems mapping with lightweight network analyses can help stakeholders evaluate interventions, identify monitoring priorities, and support adaptive decision-making in data-poor fisheries.

Introduction

Systems thinking has been applied to complex challenges for more than five decades, offering a perspective and set of tools for understanding system structure, anticipating system behavior, and identifying high-leverage opportunities for intervention (Arnold & Wade 2015; Monat & Gannon 2015). At its core, systems thinking involves problem articulation, dynamic hypothesis creation, and iterative model refinement, supporting explanation and learning rather than prediction (Sterman 2020). Dynamic hypotheses formalize stakeholders' mental models about feedback processes and non-linear relationships that drive system behavior, and their development benefits from collaborative processes that reveal diverse knowledge, test assumptions, and refine system boundaries (Vennix 1996).

Participatory approaches have become central to systems thinking because they enable stakeholders to collaboratively develop dynamic hypotheses and network models. Group model building and related participatory methods foster shared understanding, reduce conflict, and improve the legitimacy of model outcomes by actively engaging stakeholders(e.g., Davies et al. 2015; Davila et al. 2018). These approaches reflect a broader shift in sustainability science toward co-production and collaborative knowledge generation, in which system models serve not only as analytical tools but also as mechanisms for dialogue, collective learning, and joint decision-making.

Food systems present a particularly compelling application for systems thinking, yet adoption remains limited. One review found that fewer than 15% of agri-food models used system dynamics or agent-based approaches (Monasterolo et al. 2016). Several factors constrain broader adoption, including data scarcity, the tendency of individuals to simplify complex systems (Kahneman 2013), and institutional structures that favor siloed decision-making over holistic, iterative learning (Beasley 2012). Despite these barriers, systems approaches have successfully addressed multifaceted sustainability challenges across a range of sectors, including urban water management, circular resource systems, and national energy transitions (Seng & Gilbert 2008; Barnabè & Nazir 2022; Lund et al. 2022).

Within marine fisheries and social–ecological systems, participatory systems thinking has shown considerable promise. Participatory qualitative network models and related modeling approaches have been used to explore management scenarios, identify leverage points, and assess system resilience (e.g., Dambacher et al. 2007; Marzloff et al. 2016; Gourguet et al. 2021; Magel & Francis 2022; Ward et al. 2025). These studies demonstrate the value of stakeholder engagement in conceptual model development and scenario exploration while highlighting persistent challenges, including making systems approaches accessible to practitioners, translating qualitative models into semi-quantitative analyses, and generating outputs that directly inform management decisions.

These challenges are particularly acute in small-scale fisheries, where sustainability outcomes emerge from interactions among biological, social, governance, and market processes, and where governance is increasingly shifting toward participatory and co-management arrangements (Gelcich 2014; Leite & Pita 2016). Most small-scale fisheries operate in data-poor environments (Pita et al. 2019), limiting opportunities for parameter-intensive modeling approaches. Furthermore, overfishing and compliance challenges typically arise from multiple interacting behaviors across supply chains rather than from single, isolated drivers, making it difficult to identify interventions that are both effective and feasible. Together, these challenges highlight the need for systems approaches that are analytically robust, accessible to non-specialists, and capable of directly informing management decisions in data-limited contexts.

To address this need, we developed a practical systems-thinking framework that combines participatory network model development, dynamic hypothesis refinement, and lightweight network analyses for data-poor fisheries. The framework integrates a structured participatory workflow with an online platform that enables stakeholders to co-develop network models, evaluate intervention pathways, and identify monitoring indicators for adaptive management. We demonstrate the framework in two small-scale octopus (*Octopus mimus*) fisheries within the Humboldt Current Ecosystem of Peru and Chile. Specifically, we show how collaborative model development, stochastic token diffusion modeling, and network centrality analysis can support stakeholder engagement, evaluate intervention pathways, identify monitoring priorities, and generate actionable insights for improving fisheries sustainability.

Methods

Study Context. We examined the small-scale octopus *(Octopus mimus*) fisheries of Chile and Peru, which share similar ecological, regulatory, and socio-economic characteristics (Guevara-Carrasco & Bertrand 2017; Ibáñez et al. 2024). Both are considered fully exploited, dominated by artisanal divers and

subject to seasonal closures, minimum landing sizes, and formal entry restrictions, though informal harvesting remains widespread (IMARPE 2023; SUBPESCA 2024; Cubillos et al. 2025). Both fisheries are strongly influenced by interannual environmental variability associated with the El Niño–Southern Oscillation and are relatively data-poor, making traditional stock assessments and parameter-intensive system dynamics models difficult or impossible to apply (Rocha & Vega 2003; Markaida & Gilly 2016; Ibáñez et al. 2024; but see Cubillos et al. 2025). In both countries, researchers, practitioners, and fishers are actively engaged in efforts to improve sustainability (e.g., REDES 2023; Aqua 2024).

Our methodological workflow comprised four interconnected steps: (1) participatory network model development and refinement, (2) stochastic token diffusion simulations to evaluate interventions, (3) network centrality analyses to identify monitoring indicators, and (4) stakeholder interpretation and validation of model outputs (Fig. 1). Although presented sequentially, the workflow was intentionally iterative, allowing repeated refinement of the causal models throughout the participatory process.

Participatory Network Model Development & Goal Setting. We used causal loop diagrams (CLD) to elicit and structure knowledge about the octopus fishery systems. CLDs represent a form of qualitative network models in which system variables are connected through signed, directed relationships that highlight reinforcing and balancing feedback processes (Sterman 2020).We developed the CLDs using an iterative mixed-methods approach. (Dhirasasna & Sahin 2019). First, we conducted a literature review, synthesizing current knowledge of the fisheries, and identifying gaps to guide primary research. Second, we conducted semi-structured interviews in Peru (n = 42) and Chile (n = 31) with stakeholders along the supply chain. We grounded our case study in two locations: southern Peru with a focus on Ilo (Moquegua region) and northern Chile between the cities of Tocopilla and Caldera (See Supplementary Materials). Both locations have high levels of octopus landings over the past decade and, consequently, are important areas for fishing communities. Interviews included fisheries officers, octopus fishers, intermediaries, managers from processing and export plants, exporters, scientists, and practitioners. Interviews explored fishing practices, commercialization, processing, governance, compliance, enforcement, knowledge, environmental variability, and perceptions of sustainability. Third, we facilitated a structured workshop in each country. Workshop participants were a subset of interviewees (n = 19 in Peru, n = 11 in Chile). Workshops focused on collaboratively identifying the principal sustainability challenges and the factors participants believed needed to change to improve fishery sustainability.

Using the results, we constructed preliminary CLDs for the two fisheries. To support interpretation and discussion, each node was categorized into a domain: biology, environmental, economic–markets, management, or social. In addition to mapping sign and direction, we assigned each relationship a qualitative strength (low, medium, or high) based on consensus reached through the iterative workshops. Last, we facilitated an additional three workshops in each country. The goal of these workshops was to refine and validate the CLDs to reach a shared representation of the system, and to reconfirm key factors that participants believed must change to improve fishery sustainability (hereafter, *goal nodes*). During these workshops the systems platform was introduced, and participants were able explore interventions and monitoring scenarios (see below). Interviews and workshops were approved by Pontificia Universidad Católica de Chile ethics committee (180820004).

Systems Platform. To operationalize the methodological framework (Fig. 1), we developed an online platform (https://www.ripplemaps.org/dashboards). The platform serves three primary functions. First, it provides a simple interface to explore the CLD and its diagnostics. This includes options like visualizing feedback loops and filtering maps by domains. The underlying data to generate the CLD is stored in a human-readable spreadsheet that lists the nodes and their relationship to each other (see Supplementary Materials). Second, it allows users to test interventions using a token diffusion model (see below). Last, it identifies highly central nodes that are potential monitoring candidates (see below). The platform code, including the token diffusion and centrality analyses, is available on GitHub (Advanced Conservation Strategies 2026).

Evaluate Interventions. Causal Loop Diagrams (CLDs) are powerful for conceptualizing system structure but are limited in their ability to evaluate how changes propagate through a network. Many studies apply loop analysis, which converts a CLD into a signed matrix to test qualitative predictions or compare scenarios (e.g., Puccia & Levin 1985; Dambacher et al. 2007). Loop analysis primarily asks, *"In which direction will variables change?"* Our diffusion model addresses a complementary question: *"Where do intervention effects propagate, and how strongly?"*

The diffusion model begins with a configurable number of tokens assigned to one or more nodes in the network. Tokens are abstract units representing the influence of an intervention introduced at specific locations within the network. They do not correspond to a specific quantitative measure (e.g., funding or effort) but instead provide a means of simulating how intervention effects propagate through the network. The simulation unfolds over a series of discrete time steps. During each time step, each token has a probability of moving to a connected node based on the structure of the network. The probability of token movement is stochastic but weighted by relationship strength (i.e., 10%, 20%, and 30% for weak, medium, and strong links, respectively), allowing stronger relationships to exert greater influence on diffusion dynamics. Because empirical estimates of relationship-specific transition probabilities were unavailable, these values were selected to distinguish relative relationship strengths while preserving stochastic propagation, rather than to represent empirically estimated transition rates. The sign of each token movement is determined by the polarity of the edge (i.e., positive or negative), such that tokens traversing negative relationships invert their effect on the receiving node. Consequently, intervention effects preferentially propagate through stronger relationships, although the pathways and cumulative impacts remain stochastic.

As the simulation runs, we tracked the cumulative number of times a token arrives at each node, which we refer to as an *impact score*. Each arrival increases or decreases the impact score by one depending on the polarity of the relationship through which the token traveled. This metric records the cumulative history of token arrivals, not just the current state, and is useful for identifying nodes that are repeatedly activated through positive or negative influence relative to the initial token allocation. For example, allocating tokens to decrease the magnitude of a given node may generate positive effects (increasing magnitude) in some parts of the system and negative effects (decreasing magnitude) in others. For the goal nodes (i.e., octopus abundance and fisher compliance, see below), positive impact scores indicate movement in the desired direction (i.e., increased abundance or compliance), whereas negative scores indicate movement away from the desired state. The resulting impact score therefore provides a relative measure of positive or negative influence at each node.

Table 1. Four interventions applied to the octopus (*Octopus mimus*) fisheries in Peru and Chile. Each intervention targeted specific node(s) in the causal loop diagrams. Brackets show the directionality of the target node from the intervention (i.e., increase [+] or decrease [-]).

Intervention	Description	Peru target nodes	Chile target nodes
Increase formalization	Focused on promoting fisher registration and licensing to decrease the number of unformalized fishers.	1) [-] Unformalized fishers	1) [-] Unformalized fishers
Increase traceability	Focused on providing verifiable information on *what* (i.e., product), *where* (i.e., from landing to final destination), and *when* (i.e., timing through chain of custody) of the fishery.	1) [-] Octopus landings from restricted areas 2) [+] Information for improving management	1) [-] Product stockpiling by processing plants 2) [-] Offseason octopus landed 3) [+] Information for improving management
Improve co-management	Focused on supporting co-management activities, including fishing effort, via collective actions of the fishers.	1) [+] Organizational performance of fisher associations 2) [-] Fisher effort	1) [+] Collective actions 2) [-] Fisher effort
Improve knowledge	Focused on providing information to improve fishers' knowledge on the sustainable management of the fishery.	1) [+] Knowledge	1) [+] Knowledge

We selected four interventions that workshop participants were either already implementing or were interested in pursuing. For each intervention, participants identified the specific target nodes affected (Table 1). We simulated each intervention independently and all four interventions in combination, allocating 100 tokens per simulation. Tokens were distributed equally among the intervention's target nodes. Because of stochasticity in token movement, each intervention was simulated 25 times and run for 1,000 time steps. Temporal trajectories were summarized using the median impact score across simulation runs, with shaded ribbons representing the interquartile range (i.e., 25th–75th percentiles).

To contextualize the magnitude of these effects, we compared the median impact score of each goal node to the distribution of impact scores across all nodes in the network. This provides a relative measure of how strongly each intervention influenced the focal outcomes compared to its influence across the system as a whole.

Inform monitoring. Network centrality quantifies the relative importance of a node based on its position within the network (Freeman 1978). We identified potential monitoring indicators using three complementary centrality metrics (Table 2; Lü et al. 2016; Rodrigues 2019). These metrics were selected to capture distinct dimensions of the overall system state (indegree), system drivers (outdegree), and system-wide responders (closeness). To enable comparison across metrics with different scales and distributions, centrality values were converted to ordinal ranks, with a rank of 1 indicating the highest relative importance within each metric.

Table 2. Description of the three centrality metrics selected for their potential monitoring value.

Metric	Description	Monitoring value
Indegree - *system state*	Measures the number of incoming links directed toward a node. It reflects how many other nodes directly influence or affect a given node.	Nodes with high in-degree integrate influences from multiple parts of the system. As a result, they can serv
Outdegree -*system drivers*	Measures the number of outgoing links directed from a node to other nodes. It reflects how many other nodes a given node can directly influence or affect.	Nodes with high out-degree act as system drivers, exerting influence over many other system components processes.
Closeness - *system responders*	Measures how close a node is to all other nodes based on the shortest path distances. It reflects how quickly a node can interact with or be influenced by all other nodes in the system.	Nodes with high closeness can function as system-wide responders, as they are well-positioned to rapidly

Results

Build a participatory system map and define goal nodes. The iterative process of literature review, interviews, and workshops produced consensus causal maps for both fisheries (Fig. 2). Although the Chilean and Peruvian maps shared many structural features, several important differences emerged. Most notably, product stockpiling by processing plants was identified only in Chile, where it was perceived to facilitate the purchase and sale of illegally harvested octopus during seasonal closures. Both causal maps contained several reinforcing feedback loops related to de facto open-access fisheries, debt traps, the normalization of illegal markets, social mobility, and sustainability knowledge and action. Overall, the Peruvian network contained more nodes and a greater number of strong relationships than the Chilean network (see Supplementary Materials). Despite these structural differences, workshop participants in both countries identified the same two priority sustainability goals: increasing octopus abundance and improving fisher compliance with seasonal closures and the 1 kg minimum landing size (hereafter, octopus abundance and fisher compliance; Fig. 2).

Evaluate Interventions. Token diffusion simulations revealed clear differences in the magnitude, timing, and variability of intervention effects across outcomes and countries (Fig. 3). Overall, intervention effects propagated more strongly through the Chilean network than the Peruvian network, producing larger and more persistent impact trajectories, particularly for fisher compliance and late-stage abundance dynamics. Across most simulations, impact scores increased rapidly during the early time steps before either stabilizing or continuing to accumulate depending on the intervention and network structure.

Traceability consistently generated the strongest and most rapid improvements in fisher compliance in both countries. Compliance trajectories increased steeply during the first 200–300 time steps before stabilizing at substantially higher impact scores than all other interventions (Fig. 3). In contrast, formalization produced only weak compliance responses, particularly in Peru, whereas co-management and knowledge interventions generated more gradual but sustained improvements.

Responses of octopus abundance differed from those of compliance. In Peru, all interventions produced broadly similar abundance trajectories characterized by high variability and limited separation among scenarios. In Chile, abundance responses were stronger overall and continued increasing throughout much of the simulation period, particularly under the knowledge, traceability, and combined-intervention scenarios (Fig. 3).

Uncertainty also varied among interventions. Knowledge- and co-management-based interventions exhibited the widest uncertainty bands, particularly for abundance in Chile, indicating greater variability in the pathways through which intervention effects propagated. By comparison, traceability produced relatively consistent responses across simulation runs.

To place these effects in the context of the broader network, we compared the impact scores of the goal nodes with the distribution of impact scores across all nodes at the end of each simulation (t = 1,000). In both countries, octopus abundance and fisher compliance frequently ranked among the most strongly affected nodes, often exceeding the upper quartile of the system-wide impact score distributions (Fig. 4). This pattern was most pronounced for fisher compliance under the traceability intervention and for the combined-intervention scenario, indicating that intervention effects were concentrated on the stakeholder-defined goal nodes rather than distributed evenly across the network. Consistent with the temporal trajectories, the Chilean network exhibited broader impact-score distributions and higher goal-node impact scores than the Peruvian network, indicating stronger propagation of intervention effects. Across both countries, interventions generated both positive and negative impacts throughout the networks, reflecting the diverse pathways through which intervention effects diffused.

Inform monitoring. Centrality analyses revealed both shared and country-specific patterns in potential monitoring indicators (Fig. 5). Although several highly central nodes (e.g., illegal trade, fisher compliance, and total number of fishers) would be difficult to monitor directly, many other highly ranked variables represented practical and relatively low-cost indicators of broader system dynamics.

Fishing and market variables consistently ranked among the strongest candidates for monitoring overall system state. In Chile, total landings and octopus landing price ranked highest, whereas fishing effort and landing price were the leading system-state indicators in Peru. Octopus landing price was also the highest-ranked system driver in Peru, followed by government operational capacity. In Chile, fishers' concern for sustainability ranked highest as both a system driver and a system responder (Fig. 5).

Socioeconomic and export-related variables also emerged as important monitoring candidates, although their relative importance differed between countries. In Chile, debt, temporal discounting, and fishers' concern for sustainability ranked among the most influential or responsive nodes. In Peru, West African octopus exports to European Union markets, processing quality, and export-compliant octopus landings ranked highest among system responders (Fig. 5). Together, these results suggest that market dynamics, governance capacity, and fisher behavior may provide informative indicators of broader system change.

Discussion

Systems thinking approaches to sustainability have several advantages, including being more adaptive, holistic, transparent, and evidence-based (Mahajan et al. 2019). Despite these advantages, systems approaches are often difficult to operationalize in practice, particularly when moving beyond qualitative analyses such as conceptual system mapping. The challenge is common enough that the colloquial expression *spaghetti syndrome* describes system models that become so complex that they are difficult to interpret or translate into actionable recommendations (Senge 1997; Checkland 1999). Practitioners working in fisheries and food systems therefore have limited access to systems-based tools that are both analytically useful and accessible within participatory decision-making contexts. Our study addresses this gap by demonstrating a practical framework that integrates participatory causal mapping, lightweight network analyses, and interactive visualization into a single workflow for exploring interventions and monitoring strategies in data-poor fisheries.

A major strength of the approach was its ability to support collective deliberation around system structure and intervention pathways. Collaboratively developing causal maps encouraged participants to debate system boundaries, identify important feedback loops, and discuss assumptions regarding the mechanisms through which interventions influence fisheries sustainability. Similar benefits have been documented in other participatory systems approaches (Mahajan et al. 2019). The participatory process also enabled stakeholders to share perspectives and values, collaboratively define goal nodes, and identify areas of convergence despite differing interests. In particular, focusing discussions on shared sustainability outcomes appeared to help participants move beyond sectoral disagreements and engage more constructively in exploring holistic solutions.

The token diffusion model provided an additional layer of systems exploration by allowing participants to simulate how interventions propagated through the networks. Unlike loop analysis, which primarily evaluates the direction of system responses, the diffusion model helped participants explore where intervention effects traveled, how strongly they accumulated, and which nodes were most responsive. The approach allowed participants to compare individual interventions against combinations of interventions while simultaneously considering impacts on multiple goal nodes and other parts of the system. Many participants were particularly interested in understanding ancillary benefits and trade-offs across the broader network rather than focusing exclusively on predefined sustainability targets. Comparing the responses of stakeholder-defined goal nodes with the broader distribution of impacts across the network further helped participants distinguish interventions that broadly influenced the system from those that preferentially affected the outcomes they collectively prioritized. By linking participatory causal mapping with dynamic network analyses, the framework encouraged stakeholders to engage more deeply with system complexity while providing a transparent basis for comparing intervention strategies.

The intervention simulations revealed substantial differences in both the magnitude and timing of effects on octopus abundance and fisher compliance. Across both countries, traceability consistently generated the strongest and most rapid increases in compliance, suggesting that interventions targeting information flows, accountability, and market transparency may represent influential leverage points in small-scale octopus fisheries. In contrast, co-management and knowledge-based interventions produced slower but progressively increasing effects, indicating that governance and learning processes

may require longer time horizons before system-wide impacts emerge. Interestingly, all interventions tested produced relatively similar effects on octopus abundance, whereas fisher compliance responded strongly only to interventions associated with traceability. These results suggest that ecological outcomes such as abundance may respond to multiple pathways of influence, whereas behavioral outcomes such as compliance may depend on more specific and direct interventions.

The simulations also highlighted differences between Peru and Chile despite broad similarities in the fisheries systems. The participatory causal maps shared many common structural features, suggesting important cross-country commonalities within octopus fisheries of the Humboldt Current Ecosystem. At the same time, differences in network structure and analytical outputs revealed important place-based nuances. Chile generally exhibited larger and more persistent impact trajectories than Peru, suggesting stronger reinforcing dynamics or greater network connectivity. This pattern is consistent with structural differences between the two networks: despite having fewer nodes, the Chilean map exhibited higher network density, which may facilitate faster and more persistent propagation of intervention effects. Several Chilean trajectories continued increasing throughout the simulation period, whereas Peru trajectories more frequently approached asymptotic behavior. Additionally, certain variables emerged only within specific national contexts. For example, stockpiling of octopus by processing plants emerged in the Chilean causal map and was identified as a potential leverage point for improving compliance. These findings highlight the value of systems approaches for capturing context-specific dynamics.

Our centrality analyses suggest that systems thinking approaches can help identify strategic monitoring indicators. Although some highly central variables may be difficult or expensive to monitor directly (e.g., illegal trade), several feasible socioeconomic- and market-related variables consistently ranked highly across centrality dimensions. Variables such as landing price, total landings, debt, fishers' concern for sustainability, and processing quality emerged as potentially informative indicators of broader system dynamics. Importantly, the approach stimulated discussions among participants regarding the need to monitor portfolios of indicators rather than relying on single measures of fisheries performance. Because these indicators emerge from the network structure itself, they provide a transparent rationale for monitoring variables that integrate biological, social, governance, and market dynamics rather than relying solely on conventional fisheries metrics. This shift toward systems-oriented monitoring is increasingly recognized as important for adaptive governance in complex social-ecological systems (Selomane et al. 2019).

The workshops also demonstrated the importance of accessible analytical tools and visualizations in participatory systems processes. Applying relatively simple and transparent network analyses in real time helped participants interrogate the causal maps, compare interventions, and develop a shared understanding of fisheries dynamics. Effective visualizations appeared particularly important for reducing frustration associated with complex systems analyses and for helping participants distill actionable insights from highly interconnected networks. More broadly, the approach promoted iterative learning by enabling stakeholders to test assumptions, visualize alternative intervention pathways, and reconsider the relationships driving sustainability outcomes.

The governance context of small-scale fisheries provides important opportunities for embedding systems thinking approaches. Fisheries management is increasingly moving away from command-and-control approaches toward co-management arrangements that emphasize participation, knowledge integration, and adaptive governance (Gray 2006; Leite & Pita 2016). These governance structures may align well with systems approaches because they already require deliberation across stakeholder groups and scales of decision-making. Multi-stakeholder fisheries management committees, for example, could provide useful institutional settings for iterative systems mapping, intervention testing, and systems-oriented monitoring (Estévez et al. 2020). In Chile, existing legal frameworks supporting fisheries management plans and stakeholder committees provide opportunities to operationalize systems approaches in future octopus management processes (Gelcich 2014). Similarly, recent policy developments in Peru supporting management plans for benthic fisheries may create comparable opportunities (PRODUCE 2021).

Although our focus was on supporting participatory fisheries management, the framework may also have broader applications for philanthropic organizations and sustainability initiatives working in small-scale fisheries. Foundations and development organizations frequently invest in isolated projects without fully considering the broader systems in which those interventions operate. The approach may help shift planning processes toward more integrated and strategic investments by identifying leverage points, revealing interdependencies among interventions, and clarifying potential trade-offs and synergies. Because the framework supports iterative learning and adaptive monitoring, it may also help organizations align programs, strengthen collaboration, and evaluate how interventions collectively influence broader sustainability outcomes. The framework may also facilitate coordination among organizations by providing a shared systems representation against which complementary interventions can be designed and evaluated.

Several limitations should be acknowledged. First, the analytical results are fundamentally dependent on the structure and quality of the causal maps developed through the participatory process (Powell et al. 2024). Simplified maps may omit important dynamics, whereas excessively complex maps can become difficult to analyze or translate into actionable insights. Second, although the token diffusion model provides a useful exploratory framework for evaluating relative influence and propagation pathways, it should not be interpreted as a predictive forecasting model. The simulations represent stakeholder-informed system dynamics rather than empirical population or economic projections. Third, workshop participation was limited to relatively small groups of participants, which is a common challenge in participatory modeling (Jordan et al. 2018). As a result, some stakeholder perspectives may not have been fully represented, and communicating outputs to actors not directly involved in the process may remain difficult. Finally, the time, facilitation, and analytical capacity required to implement systems approaches are not insignificant and likely represent an important barrier to broader adoption in practice (Zellner & Campbell 2015).

Despite these limitations, our results demonstrate that participatory systems thinking can move beyond conceptual mapping to support practical conservation decision-making. By integrating collaborative causal mapping, token diffusion modeling, network centrality analyses, and interactive visualization, the framework enables stakeholders to explore intervention pathways, identify leverage points, prioritize monitoring indicators, and iteratively refine management strategies in data-poor fisheries. Although developed for small-scale octopus fisheries, the framework is broadly applicable to other conservation and natural resource systems where decisions must be made despite limited quantitative data and multiple interacting social and ecological processes.

Declarations

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Ethics: Interviews and workshops were approved by Pontificia Universidad Católica de Chile ethics committee (180820004).

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Figures

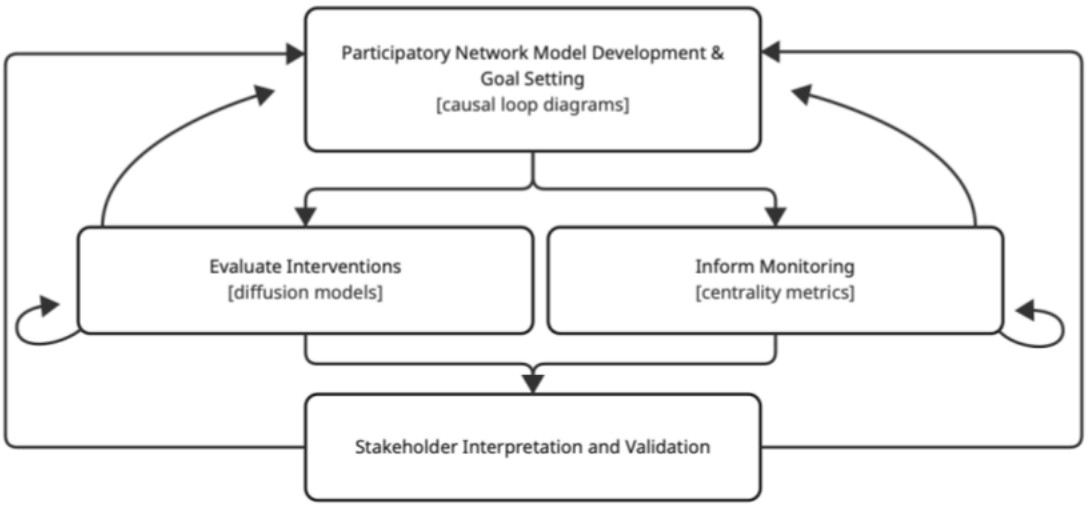


Figure 1

Methodological framework for operationalizing a system thinking approach to improve sustainability in a data-poor environment. The tools used for each step are in brackets.

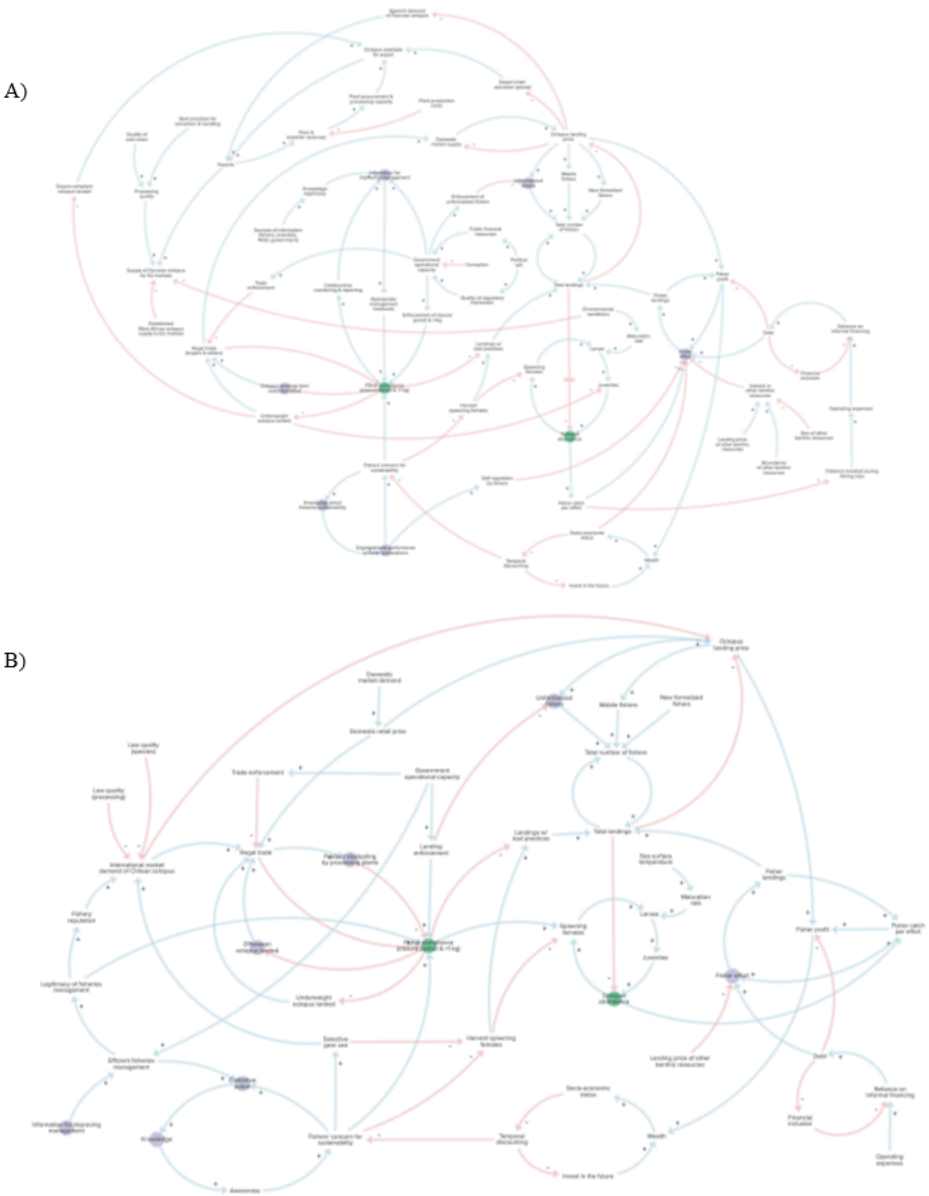


Figure 2

Collaborative causal maps of the octopus fishery (*Octopus mimus*) in A) Peru and B) Chile. Goal nodes (green) and node targeted by interventions (purple) emerged from participatory workshops. Blue lines represent positive (+) relationships, while red lines represent negative (-) relationships.

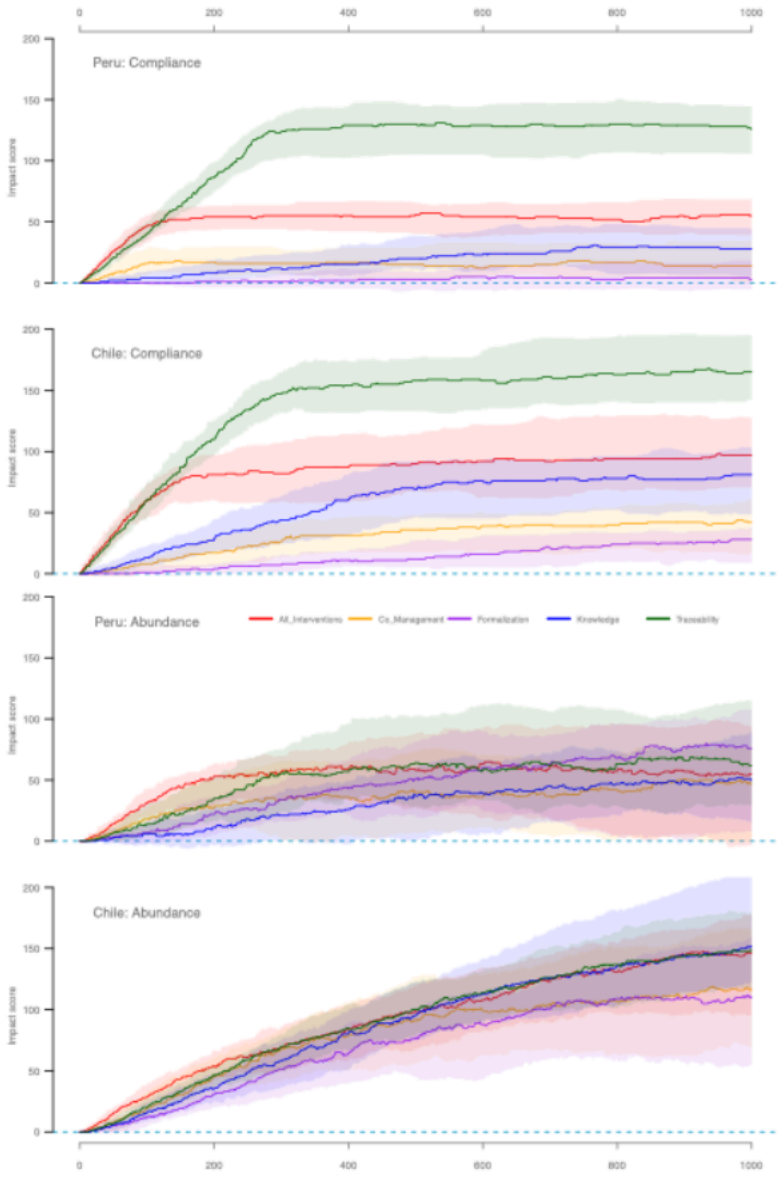


Figure 3

Temporal trajectories of median impact scores for octopus abundance and fisher compliance under five intervention scenarios in Peru and Chile. Solid lines represent the median impact score across 25 stochastic simulation runs, while shaded ribbons represent the interquartile range (25th–75th percentiles). Simulations were run for 1,000 time-steps.

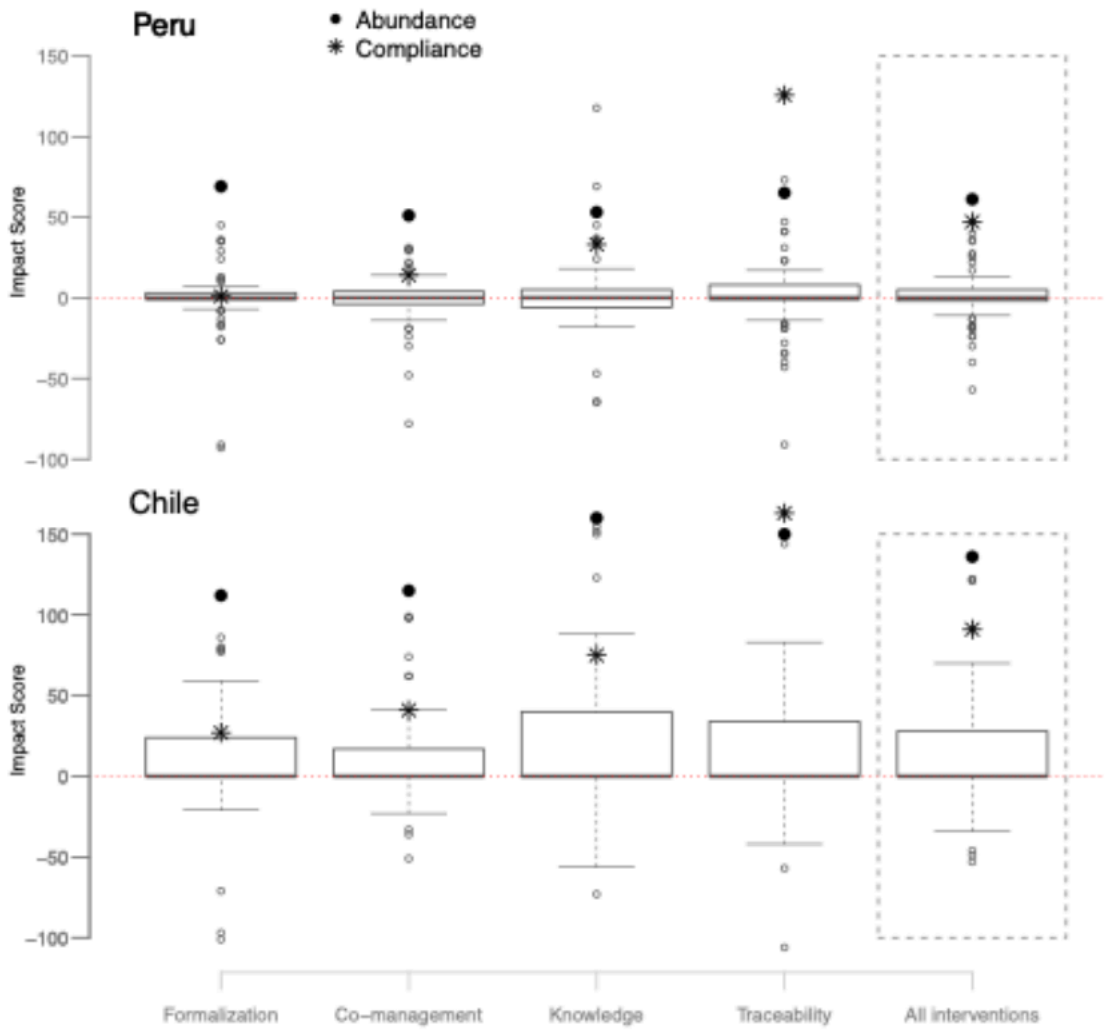


Figure 4

Distribution of impact scores across all nodes in the Peru and Chile networks at the end of the token diffusion simulations (*t* = 1,000) for each intervention scenario. Boxplots represent the distribution of impact scores for all nodes in the network across 25 simulation runs, with the center line indicating the median and boxes representing the interquartile range. Points indicate the median impact scores for the focal goal nodes: octopus abundance (circles) and fisher compliance (asterisks).

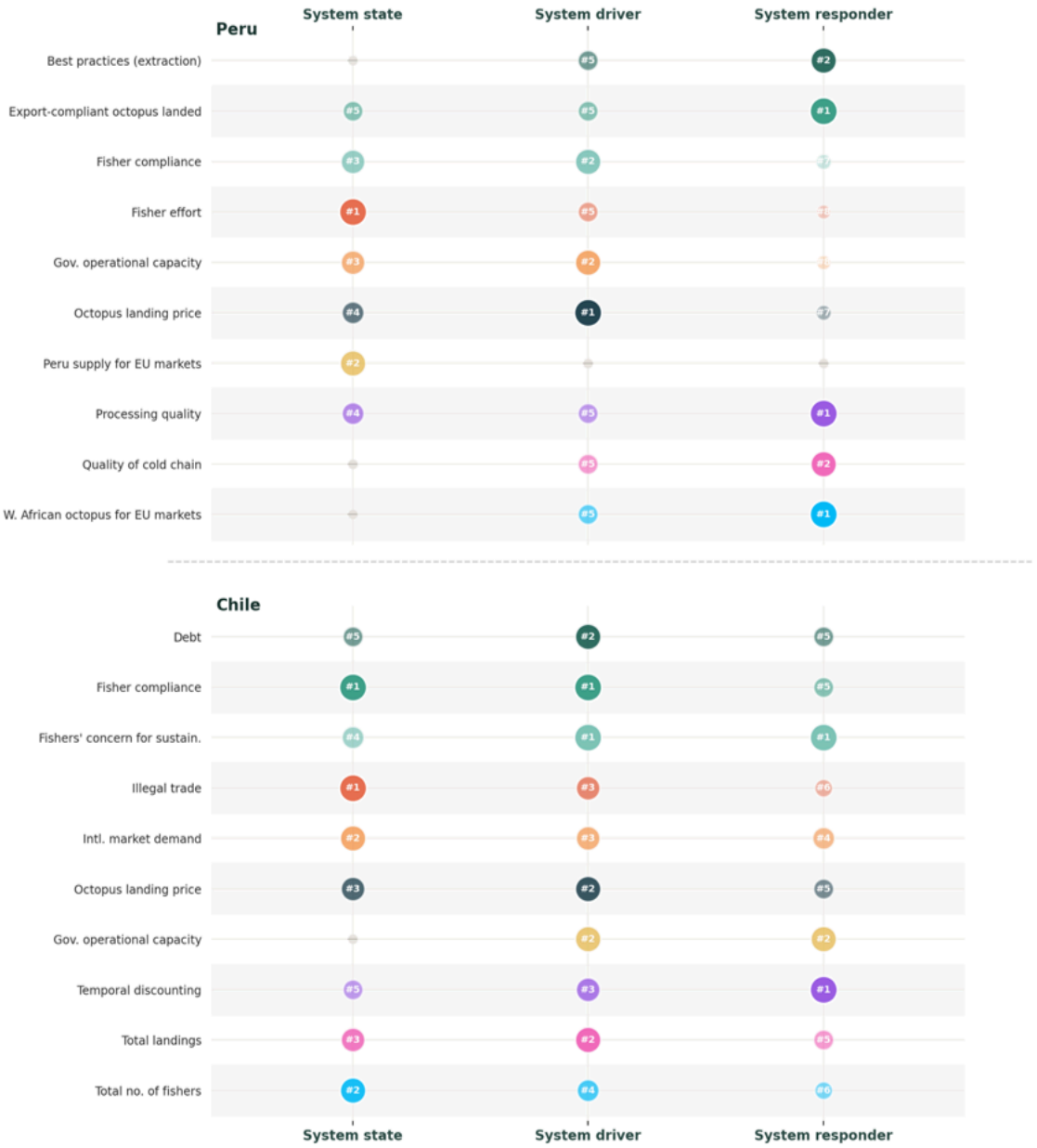


Figure 5

System nodes with high centrality that are potential monitoring targets. Nodes that ranked first or second for indegree (system state), outdegree (system driver), or closeness (system responder) are shown.

Supplementary Files

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- Supplementarymaterial.docx