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REVIEW

A novel framework for analyzing conservation impacts: evaluation, theory, and marine protected areas

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Environmental conservation initiatives, including marine protected areas (MPAs), have proliferated in recent decades. Designed to conserve marine biodiversity, many MPAs also seek to foster sustainable development. As is the case for many other environmental policies and programs, the impacts of MPAs are poorly understood. Social–ecological systems, impact evaluation, and common-pool resource governance are three complementary scientific frameworks for documenting and explaining the ecological and social impacts of conservation interventions. We review key components of these three frameworks and their implications for the study of conservation policy, program, and project outcomes. Using MPAs as an illustrative example, we then draw upon these three frameworks to describe an integrated approach for rigorous empirical documentation and causal explanation of conservation impacts. This integrated *three-framework* approach for *impact evaluation of governance in social–ecological systems* (3FIGS) accounts for alternative explanations, builds upon and advances social theory, and provides novel policy insights in ways that no single approach affords. Despite the inherent complexity of social–ecological systems and the difficulty of causal inference, the 3FIGS approach can dramatically advance our understanding of, and the evidentiary basis for, effective MPAs and other conservation initiatives.

Keywords: protected areas; impact evaluation; social–ecological systems; common-pool resources; governance; biodiversity conservation; ecological integrity; human well-being

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Introduction

Recent decades have witnessed rapid growth in the diversity, abundance, and spatial extent of environmental conservation initiatives designed to conserve biodiversity and foster sustainable development.^{1–3} National parks, hunting regulations, endangered species legislation, pollution control laws, and other traditional state-centered regulatory policies have been joined by formal systems of payments for ecosystem services,⁴ community-based management,^{5,6} environmental certification,⁷ and natural resource privatization (e.g., privately protected areas, conservation easements, and catch shares).^{8–10} Despite the growing number and diversity of conservation initiatives, the impacts of these interventions are often only poorly understood.^{11,12}

Marine protected areas (MPAs), a cornerstone of global efforts to conserve marine biodiversity and alleviate coastal poverty, typify the proliferation of conservation initiatives. Also known as marine reserves, sanctuaries, managed areas, and parks, an MPA is “any area of the intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment.”¹³ The number and spatial extent of MPAs have increased severalfold since 1990, accelerating in recent years, such that more than 12,000 MPAs now cover 8.4% of coastal waters and 3.4% of the global ocean.^{14,15} MPAs vary dramatically in size, regulatory restrictions, governance, and social and ecological contexts.^{16–18} MPAs are established for diverse reasons,^{19,20} often with multiple and sometimes conflicting goals: small, locally managed MPAs are often designed to enhance food security and manage data-poor fisheries,¹⁸ while large “Big Ocean” MPAs contribute to full representation of marine habitats and progress toward Convention on Biological Diversity targets for MPAs to cover 10% of the global ocean by 2020.^{14,15,21}

The ecological impacts of MPAs are highly variable, ranging from positive to negative.^{22–24} MPA establishment often increases the density, biomass, size, and diversity of otherwise-exploited species within MPA boundaries,^{23–25} with subsequent indirect impacts on other species through cascading ecological interactions (e.g., parrotfish increases, macroalgae declines, and subsequent coral recovery).^{26–28} Available evidence, although

limited, suggests that MPAs that prohibit fishing can lead to enhanced ecological resilience, including resilience to climate fluctuations,^{29,30} storm disturbance,³¹ and invasive species.³² Corresponding impacts in areas adjacent to MPAs include increased larval recruitment,³³ spillover of adult fish,^{34,35} and reduced fear behaviors among fish.³⁶ The wide variation in direction and magnitude of MPA ecological impacts has been attributed to MPA governance (e.g., MPA age, size, resource-use rules, and compliance), management capacity (e.g., staff and budget),²⁴ biophysical factors (e.g., isolation by deep water), and species traits (e.g., range or life history characteristics).^{37–40} A significant portion of the variability in ecological outcomes remains unexplained.^{23,24,41}

The social impacts of MPAs are widely debated and less well understood than their ecological analogues.^{22,42} The intended and unintended social impacts of MPAs vary across social domains,^{42,43} spatial and temporal scales,⁴⁴ and within and among social groups.^{42,45} MPA establishment reallocates property rights⁴⁶ over marine resources, thus restructuring relationships among stakeholders and transforming spatial and temporal patterns of fishing and other activities.^{47,48} In many cases, reallocation of MPA resource rights affects multiple dimensions of human well-being^{42,49} through processes mediated by the characteristics of individual resource users (e.g., gear type)^{42,44} and contextual characteristics (e.g., human population size).⁵⁰ The resulting MPA impacts on economic well-being, cultural identity, and social conflict can be positive, neutral, or negative (e.g., Refs. 43 and 51–53). Evidence suggests that MPAs significantly increase aspects of food security for most fisher subgroups,⁴² but the long-term implications of MPAs for other health outcomes remain largely unexplored.^{54,55} The magnitude and direction of MPA social impacts are frequently dependent on scale, varying at different levels of social organization.⁴⁴ Social impacts also vary in their degree of permanence,⁴³ with some more likely to manifest almost immediately (e.g., resource rights)⁴⁷ and others emerging over longer timescales (e.g., child nutrition).⁵⁴ MPAs frequently confer economic benefits and costs to those who use MPA resources; these benefits and costs are often unequally distributed among individuals, among social groups, and across space and time.^{47,56–58} MPA economic benefits may

include increased revenue from nonextractive uses and the capture of nonuse value (e.g., donations and user fees).^{59–62} Conversely, extractive users may face significant opportunity and financial costs from MPA establishment.^{58,63}

Scholars and practitioners have proposed diverse analytic frameworks for monitoring and evaluating MPAs (e.g., Refs. 64–66) and analogous conservation initiatives (e.g., Refs. 67 and 68), but three distinct approaches have gained currency: social–ecological systems (SESs), impact evaluation, and common-pool resource governance.^{69–71} An SES is an integrated system characterized by complex, interdependent, and reciprocal relationships between human society and ecosystems.⁷² Impact evaluation, by contrast, is the systematic process of assessing the causal effects of a project, program, or policy.⁷³ Common-pool resource governance refers to the system of decision-making arrangements, resource-use rights, monitoring and enforcement systems, and conflict-resolution mechanisms that shape human interactions with common-pool natural resources. To date, the relationships among these three approaches remain relatively unexplored.

To further scientific efforts to document and explain variation in the impacts of conservation initiatives, we review the relationships among key components of SESs, impact evaluation, and common-pool resource governance. In particular, we examine the SES framework for classifying social–ecological variables, the research design tenets of impact evaluation, and hypotheses derived from theories of common-pool resource governance. Using MPAs as an illustrative example, we then draw upon these three approaches to describe an integrated approach for rigorous empirical documentation and causal explanation of conservation impacts. This integrated *three-framework* approach to *impact evaluation of governance in social–ecological systems* (3FIGS) controls for alternative causal explanations, builds upon and advances social theory, and provides novel policy insights in ways that no single approach affords. We conclude with a discussion of the merits and limits of 3FIGS for evaluation of MPAs and other conservation interventions.

3FIGS conceptual foundations

Social–ecological systems framework

The SES framework is a hierarchical classification system that helps to “identify the basic working parts

and critical relationships” that characterize coupled social and ecological systems.⁷⁴ As part of the broader literature on SESs,^{75–77} the SES framework “facilitate[s] multidisciplinary efforts toward a better understanding of complex SESs”⁷⁸—particularly those involving common-pool natural resources.⁷⁴ At its most basic, the SES framework categorizes the relationships and interactions (Fig. 1; I) among specific actors (A), governance systems (GS), natural resource systems (RS), and resource units (RU)—and the social and ecological outcomes (O) that flow from these interactions. The interactions among these four subsystems (A, GS, RS, and RU) and the outcomes (O) that result from them are the products of a *focal action situation* (a situation in which inputs are transformed by multiple actors into outcomes);⁷⁴ these subsystems, interactions, and outcomes are embedded within a broader social (S) and ecological context (ECO) that may shape—and be shaped by—the SESs.⁷⁸ Each subsystem comprises a specific set of attributes (Table 1), each of which can be further disaggregated.^{74,78,79} While higher level attributes are universal to any SES, lower level attributes are specific to particular systems.^{79,80}

The SES framework provides a heuristic tool for characterizing conservation interventions and their impacts.⁷⁷ Conservation interventions are policies, programs, and projects—often novel governance systems—designed to shape the behavior of specific actors and thus conserve natural resources.⁸¹ These interactions are embedded within a broader social and ecological context that shapes—and is shaped by—the performance of the conservation intervention.¹⁶ Thus, rearranging the SES subsystems can highlight the relationships between a governance-focused conservation intervention and its impacts (Fig. 2). As a classificatory system, however, the SES framework does not provide guidance regarding the hypothesized causal relationships among variables or the research designs that one might employ to examine these relationships.⁷⁴

Impact-evaluation research design

Impact evaluation places particular emphasis on research designs that permit causal inference.^{11,73} Causal inference rests on the comparison of outcomes observed under an intervention with an estimate of what would have happened in the absence of that intervention (i.e., the counterfactual);⁸² this comparison provides an estimate of the

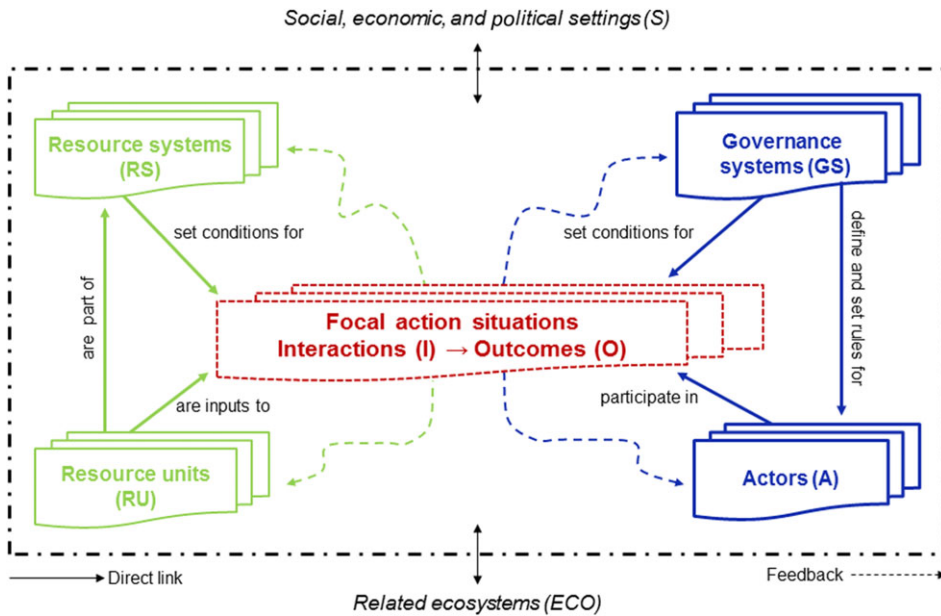


Figure 1. The first-tier variables within a social–ecological system (SES). “The subsystems are (i) resource systems (e.g., a designated protected park encompassing a specified territory containing forested areas, wildlife, and water systems), (ii) resource units (e.g., trees, shrubs, and plants contained in the park, types of wildlife, and amount and flow of water), (iii) governance systems (e.g., the government and other organizations that manage the park, the specific rules related to the use of the park, and how these rules are made), and (iv) users (e.g., individuals who use the park in diverse ways for sustenance, recreation, or commercial purposes). Each core subsystem is made up of multiple second-level variables (e.g., size of a resource system, mobility of a resource unit, level of governance, users’ knowledge of the resource system) . . . which are further composed of deeper level variables.”⁶⁸ Used with permission from McGinnis and Ostrom;⁷⁴ adapted from Ref. 68.

intended and unintended impacts attributable to an intervention.^{73,82} Causal relationships between an intervention and its impacts can be explored with experiments (where random assignment to treatment and nontreatment groups is feasible)⁸² or, more commonly in SESs, quasiexperiments that apply statistical techniques (e.g., regression discontinuity, matched comparisons, and synthetic controls)^{73,82} to control for systematic differences between treated (e.g., MPA) and untreated (e.g., non-MPA) groups. Other research designs are also employed in impact evaluation (e.g., in-depth case studies), “though the credibility of their estimates of program effects relies on how well the studies’ designs rule out competing causal explanations.”⁸³

Central to impact evaluation is the exclusion of alternative explanations for the outcomes observed in intervention sites.⁸⁴ Impact evaluations control for factors that may bias the magnitude or direction of impact estimates (e.g., attributes of the actors (A), resource systems (RS), resource units (RU), and social and ecological context (S; ECO)),⁸⁵ thus

creating analyses of paired SESs that vary only in their governance and, perhaps, in their outcomes (Fig. 3). All other subsystems (and elements) of the SES framework (e.g., GS) represent variables that researchers must control for (e.g., through randomization or statistical matching) or explicitly incorporate into analyses as explanatory variables. Where SESs processes in an intervention influence the status of outcome variables (e.g., biomass and economic well-being) in nonintervention sites, appropriate impact evaluation design must also employ methods to eliminate bias arising from either leakage (e.g., the displacement of harvest effort from intervention to nonintervention sites)⁸⁶ or spill-over effects (e.g., increased harvest in nonintervention sites due to biomass increases generated by intervention).⁵¹ At their simplest, comparative analyses of these paired SESs allow researchers to document the impacts of an intervention (e.g., Refs. 87 and 88), while emerging approaches highlight the potential to explore the mechanisms and pathways by which impacts occur

Table 1. The second-tier variables of a social–ecological system (SES)⁷⁴

First-tier variable	Second-tier variable
Social, economic, and political settings (S)	S1—Economic development
	S2—Demographic trends
	S3—Political stability
	S4—Other governance trends
	S5—Market stability
	S6—Media organizations
	S7—Technology
Resource systems (RS)	RS1—Sector (e.g., water, pasture, forests, and fish)
	RS2—Clarity of system boundaries
	RS3—Size of resource systems
	RS4—Human-constructed facilities
	RS5—Productivity of system
	RS6—Equilibrium properties
	RS7—Predictability of system dynamics
	RS8—Storage characteristics
	RS9—Location
Governance systems (GS)	GS1—Government organizations
	GS2—Nongovernmental organizations
	GS3—Network structure
	GS4—Property rights systems
	GS5—Operational-choice rules
	GS6—Collective-choice rules
	GS7—Constitutional-choice rules
	GS8—Monitoring and sanctioning rules
Resource units (RU)	RU1—Resource unit mobility
	RU2—Growth or replacement rate
	RU3—Interaction among resource units
	RU4—Economic value
	RU5—Number of resource units
	RU6—Distinctive characteristics
	RU7—Spatial and temporal characteristics
Actors (A)	A1—Number of relevant actors
	A2—Socioeconomic attributes
	A3—History or past experiences
	A4—Location
	A5—Leadership/entrepreneurship
	A6—Norms (trust-reciprocity)/social capital
	A7—Knowledge of SES/mental models
	A8—Importance of resource (dependence)
	A9—Technologies available
Action situations: interactions (I)–outcomes (O)	I1—Harvesting
	I2—Information sharing
	I3—Deliberation processes

Continued

Table 1. Continued

First-tier variable	Second-tier variable
	I4—Conflicts
	I5—Investment activities
	I6—Lobbying activities
	I7—Self-organizing activities
	I8—Networking activities
	I9—Monitoring activities
	I10—Evaluative activities
	O1—Social performance measures (e.g., efficiency, equity, sustainability, and accountability)
	O2—Ecological performance measures (e.g., overharvested, resilience, biodiversity, and sustainability)
	O3—Externalities to other SESs
Related ecosystems (ECO)	ECO1—Climate patterns
	ECO2—Pollution patterns
	ECO3—Flows into and out of focal SESs

Note: Adapted from Ref. 78.

(e.g., Ref. 89), variation in impacts within and among groups, the attributes of an intervention that foster positive (or negative) impacts, and the contexts in which an intervention is most likely to succeed or fail.^{12,90} The SES framework provides a valuable heuristic for researchers attempting to identify and control for systematic biases that might confound the relationship between interventions and outcomes, precluding causal inference. Substantial barriers to understanding the impact of interventions on SESs remain, however, given that impact evaluation provides no guidance regarding the specific variables to measure in a given SES or the hypothesized relationships among them.⁹¹

Common-pool resource governance theory
Theories of common-pool resource governance^{92–94} seek to explain the emergence, evolution, and performance of regimes governing common-pool natural resources and analogous systems. In common pool resources, use is *rival* (i.e., use by one individual diminishes the resources available to another) and *exclusion* of potential resource users is difficult or costly, creating the potential for overexploitation of scarce resources.^{95,96} Theories of common-pool resource governance have highlighted four dimensions of governance that profoundly affect the performance of regimes governing fisheries, forests, grasslands, and other common-pool resources:

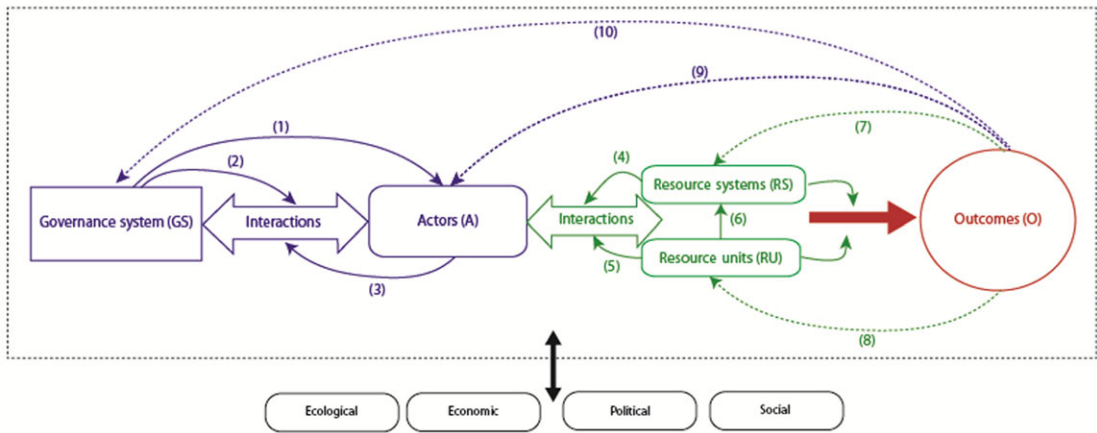


Figure 2. The first-tier variables within a social–ecological system (SES), reorganized to emphasize the causal relationships between governance systems and outcomes. Conservation interventions often represent novel governance systems that induce a causal chain of events with intended and unintended consequences, feedback loops, synergies, and trade-offs. Related ecosystems (ECO) and social, economic, and political settings (S) in Figure 1 are collectively represented here as contextual variables. Solid lines represent direct links; dashed lines represent feedback mechanisms. Numbered arrows represent links labeled in Figure 1 as (1) “set rules for,” (2) “set conditions for,” (3) “participate in,” (4) “set conditions for,” (5) “are inputs to,” and (6) “are part of.” Numbered arrows (7–10) represent feedback mechanisms.

decision-making arrangements (Table 1; GS6, GS7), resource-use rights (GS4, GS5), monitoring and enforcement systems (GS8), and conflict-resolution mechanisms.^{78,92} In each of these four dimensions, research has identified variables hypothesized to shape outcomes in specific ways (Table 2). Theories of common-pool resource governance also provide insights into the diverse factors that foster the emergence and evolution of governance regimes through collective action,⁹² highlighting the complex relationships among different components of the SES framework.⁷⁸ Indeed, many elements of the SES framework have their origins in the early analytic frameworks of the literature on common-pool resource governance.^{77,97}

Originally developed in the context of small-scale common-pool resource systems,^{92,98,99} theories of common-pool resource governance are valid starting hypotheses for predicting impacts of conservation interventions in larger and more complex SESs.^{77,78} Ostrom’s design principles for sustainable regimes,^{92,93} for example, are hypotheses to operationalize and test within an impact-evaluation research design (Fig.4). Though the large number of potential explanatory variables complicates hypothesis testing,⁹⁴ and reductionist methods may obscure emergent properties,^{74,79} careful attention to research design can help

to address these challenges.^{77,97} Thus, theories of common-pool resource governance have the potential to catalyze a substantive advance in the rigor and reach of impact evaluations.⁹¹ Likewise, rigorous research designs informed by impact evaluation may foster important insights into common-pool resource governance theory.

Operationalizing 3FIGS: MPAs as an illustrative example

MPAs illustrate the potential for an integrated three-framework approach to influence evaluation of common-pool resource governance in SESs. MPAs are an exemplar of an SES^{69,78} increasingly examined through the lens of impact evaluation^{22,43,100} and the theories of common-pool resource governance.^{16,101} However, like studies of other conservation interventions, MPA research has yet to fully integrate the research questions, methods, and study designs of impact evaluation; the principles and hypotheses of common-pool resource governance theory; and the conceptual framework of SESs. Here, we outline the potential for 3FIGS to provide an integrated approach to examining the impacts of conservation interventions, drawing upon the SES framework (Fig. 1) to identify (1) the potential ecological and social outcomes of an intervention and (2) the confounding ecological

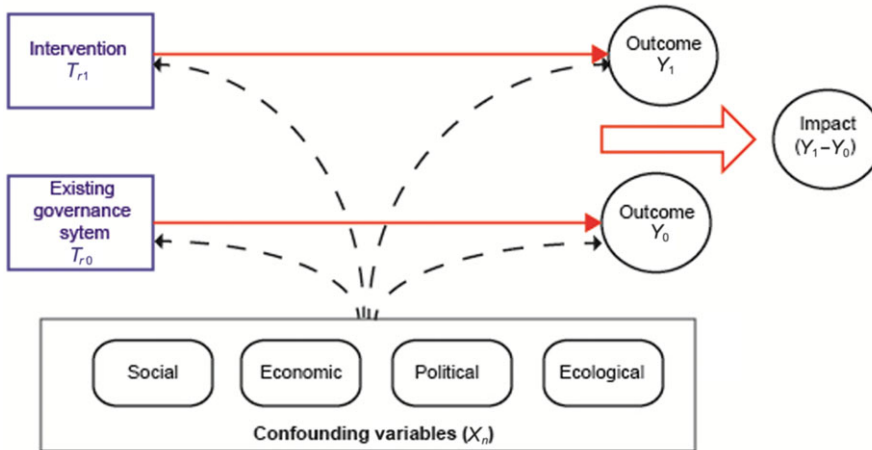


Figure 3. Directed acyclic graph (DAG) illustrating how the essential social–ecological relationships may be examined through the lens of impact evaluation. Contextual variables in Figure 2 are illustrated here as confounding variables that are explicitly controlled through research design. We use the term *impact* to denote a generic treatment effect (i.e., the causal impact of an intervention on a variable of interest).

and social processes to be controlled to obtain an unbiased estimate of MPA impacts. Having identified potential outcome variables, impact-evaluation research designs provide a methodology for documenting MPA impacts while controlling for confounding SES interactions and processes (Fig. 3). Finally, elements of common-pool resource governance, nested as differential treatments within an impact-evaluation research design, allow an examination of the mechanisms by which MPAs have ecological and social impacts (Fig. 4).

MPA governance systems^c

Governance constitutes the processes by which authority is conferred, by which authoritative decisions are made, and by which these decisions are enforced and modified.^{102–104} Governance is a principal component of SESs,⁷⁸ structuring human interactions across all levels of social organization (Fig. 2).^{104,105} Like many conservation interventions, MPAs are, essentially, novel governance systems that explicitly or implicitly define *who* may do *what*—and *where, when, and how* they may do it—with respect to a specific, spatially bounded portion of the environment (denoted by blue elements in Fig. 2).¹⁶ In many cases, MPAs are layered upon existing marine governance systems, modifying or replacing the prior governance regime.

The four principal components of MPA governance (decision-making arrangements, resource-use rules, monitoring and enforcement systems, and conflict-resolution mechanisms) directly and indirectly shape human resource-use patterns and, ultimately, the ecological and social impacts of MPAs.¹⁶ Each of these four elements may have both formal and informal components derived from diverse sources, including legal statutes, policy statements, judicial decisions, organizational practices, social norms, and cultural traditions. As a result, the *de facto* system of governance that actually governs an MPA often differs sharply from the *de jure* regime established through formal legal structures and policy processes.¹⁶ The *de facto* system of rules and the processes through which these rules are developed, implemented, and adapted over time significantly influence MPA impacts. Specific governance characteristics—known as *design principles*—are associated with long-term sustainability in institutions governing common-pool resources,⁹² such as conservation interventions.^{22,106}

MPA decision-making arrangements specify the rights of individuals or groups to make choices regarding other aspects of MPA design and management. Decision-making arrangements shape rules governing resource use by defining the interests represented and manifested in policymaking processes. Collective-choice rules (Table 1; GS6) determine, for example, who may participate in making decisions

^cThis section is adapted from and builds upon Ref. 16.

Table 2. Domains of marine protected area (MPA) governance, hypothesized attributes of successful MPA governance, and illustrative indicators to monitor^{16,22,130}

Domain	Hypothesized attribute	Illustrative indicator
Decision-making arrangements	Resource users participate in decision making	Proportion of user groups participating in decision to establish MPA
	Resource user may self-govern resource use	Proportion of users whose right to self-organize is minimally recognized by government
Resource-use rights	Resource users defined clearly	Proportion of important users subject to specific appropriation rule
	Resources defined clearly	Proportion of MPA boundary clearly demarcated to users
	Resource user costs and benefits roughly proportional	MPA cost–benefit ratio to resource users
Monitoring and enforcement systems	Resource user rights linked to local conditions	Proportion of MPA rules context dependent
	Monitors assess resource conditions	Ecological monitoring patrol frequency
	Monitors assess user behavior	Compliance monitoring patrol frequency
	Monitors are resource users or are accountable to users	Sanctions for failing to monitor resource
	Sanctions for noncompliance likely	Frequency of sanctions for noncompliance
	Sanctions for noncompliance graduated	Mean types of sanctions levied for noncompliance
Conflict-resolution mechanisms	Sanctions for noncompliance context dependent	Mean number of contextual factors considered when imposing sanction for noncompliance
	Conflict-resolution mechanisms accessible to users	Mean time/cost to resolve conflict

Note: Domains, hypothesized attributes, and illustrative indicators derived from theories of common-pool resource governance.^{92,93}

and who may not (e.g., government officials and resource users), how decision makers are selected for their positions (e.g., elected or appointed), and how decisions are made (e.g., consensus or majority vote).⁹² Constitutional-choice arrangements (GS7) define how decisions are made regarding the configuration of collective-choice arrangements;⁹² these higher order social institutions shape both MPA governance and impacts by defining how site-level rules are made and who makes them.¹⁶ Subtle differences in the rules that govern MPA decision making may have significant impacts on MPA design, implementation, and evaluation (e.g., U.S. National Marine Sanctuaries).¹⁰⁷ Governance regimes that recognize the rights of resource users to participate in decision making and to self-govern tend to be more effective than those that centralize authority in a few individuals or actors (Table 2).⁹²

Rules governing resource use (Table 1; GS4, GS5) are the second principal element of MPA governance. Resource-use rules (denoted by arrow 1

in Fig. 2)—including laws, regulations, formal and informal policies, codes of conduct, and social norms—specify the rights of individuals or groups to access and appropriate resources. Held by individuals, groups, organizations, or the state, these rights establish standards for interactions among individuals and between individuals and the marine environment (“actors” and “interactions” in Fig. 2). Infinite possible configurations of resource-use rules exist, ranging along a continuum from “open access” (i.e., no rules/any and all uses) to a complete prohibition on human activities. Rules may apply to specific locations, times, resources, and actors. Individuals or groups may be defined by actors’ identities, geographic proximity, tenure, activity type (e.g., consumptive versus nonconsumptive), intent (e.g., targeted species, recreational versus commercial activity), or practices (e.g., fishing gear). Consequently, the rules governing marine resources may shape the direction, magnitude, and distribution of MPA impacts. Four attributes

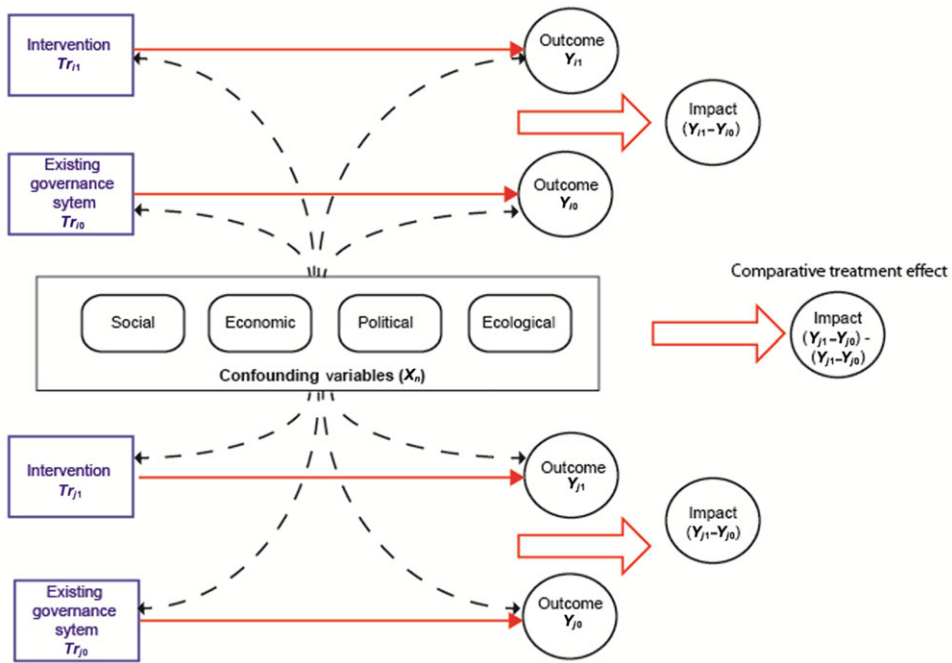


Figure 4. Alternative hypotheses from theories of common-pool resource governance examined through the lens of impact evaluations. The relative treatment effect of paired conservation interventions, representing the single null (Tr_i) or alternative common-pool resource hypotheses (Tr_j) (e.g., protected area without active and accountable monitoring versus protected area with active and accountable monitoring), can be examined through impact evaluation. Contextual variables in Figure 2 are illustrated here as confounding variables that are explicitly controlled through research design. We use the term *impact* to denote a generic treatment effect (i.e., the causal impact of an intervention on a variable of interest). “Comparative impact” refers to the net difference in treatment effects between conservation interventions i and j .

of resource-use rights are associated with sustainable governance systems: (1) clearly defined resource users, (2) clearly defined resources, (3) contextually appropriate resource-use rights, and (4) roughly proportional impacts on resource users.^{92,93} Unclear boundaries may limit the ability of resource users to develop appropriate rules and monitor compliance. Incongruent rules or those with disproportionate effects on particular social or economic groups may undermine compliance.⁹² Ecologists also note that MPA age, size, location, spatial configuration, and fishing prohibitions—all manifestations of resource-use rights—often shape MPA impacts (Table 2) (e.g., Refs. 38, 39, and 41).

MPA monitoring systems (Table 1; I9, GS8) seek to track changes in the state of MPA-associated social and environmental systems. MPA monitoring systems vary in what they measure and who does the measuring, as well as where, when, and how measurements are made. Monitoring can provide decision makers with insights on social and

ecological conditions (ambient monitoring), track the progress of management actions toward a specified goal (performance measurement), or document the intended or unintended impacts of MPA establishment (impact evaluation).⁹⁰ In addition, the involvement of resource users and other non-scientists in formal data collection and analysis (i.e., participatory monitoring) may also provide a mechanism for increasing awareness, improving resource management, and empowering communities.¹⁰⁸ In practice, relatively few MPAs have comprehensive monitoring systems; resource users, managers, and other stakeholders often informally monitor environmental and social indicators to assess MPA performance (Table 2).¹⁶

Sanctioning systems (Table 1; GS8) attempt to increase compliance with rules governing resource use by monitoring user behavior (I9) and punishing those engaged in prohibited activities. By increasing the severity and likelihood of sanctions and thus raising the opportunity cost of

noncompliance, enforcement systems act directly on resource users to foster adherence to established rules. Research highlights six attributes of monitoring and sanctioning systems that are hypothesized to enhance performance of MPAs and other natural resource governance regimes: monitoring systems that assess (1) resource conditions and (2) user behavior; and (3) ensure accountability to users; and enforcement systems with (4) meaningful but (5) graduated and (6) context-dependent sanctions, which ensure that the punishment fits the crime (Table 2).⁹²

Lastly, conflict-resolution mechanisms are formal and informal processes for resolving disputes. Conflict-resolution mechanisms permit information exchange, clarification of resource-use rights, and adjudication of disputes related to decision making, resource use, monitoring, and enforcement. Though not highlighted in the SES framework, readily accessible and low-cost conflict-resolution mechanisms enhance regime performance by mitigating social conflict and thereby minimizing resource overexploitation and dissipation of benefits from common-pool resources.⁹² Conflict-resolution mechanisms also enhance MPA performance by giving voice to aggrieved parties and acknowledging their concerns, which increases the legitimacy of MPA rules and regulations. Evidence suggests that (1) rapid, (2) low-cost, and (3) easily accessible conflict-resolution mechanisms are more likely to facilitate negotiation between actors than more complex, expensive, or remote systems (Table 2).⁹²

Resource-use patterns: actors and their interactions

MPA governance regimes (Fig. 1; GS) directly and indirectly structure interactions (I) between humans (A) and marine species (RU) and ecosystems (RS) by defining the rules governing resource use and by shaping rates of compliance with these rules. These patterns of consumptive and nonconsumptive resource access, use, and appropriation (shown in blue in Fig. 2; I1) may be characterized by five sets of variables: the resources used; demographic attributes of the users; location of use; timing of use; and mode of use.¹⁰⁹ (In other words, *what* is being used *by whom*, *where*, *when*, and *how*?) The demographics of resource use—who uses resources—can be characterized by both the

number of users (A1) and their social attributes (A2; e.g., gender, age, class, place of residence, education, culture, ethnicity, and religion), though not all of these variables will be salient in all cases. Actors' past experiences (A3), mental models (A7), and degree of resource dependence (A8) also shape resource-use patterns. Location (A4) and timing of use also define resource-use patterns in simple but important ways. Lastly, the mode (A9) and intensity of resource use, including both consumptive (e.g., fishing) and nonconsumptive practices (e.g., dive tourism), are key characteristics of actors' resource-use patterns.¹¹⁰ Resource-use patterns may vary in any one or all of these dimensions; these differences may lead to significant differences in the biological and social impacts of MPAs.^{37,109}

Resource systems, units, and interactions

Resource-use patterns are structured by characteristics of resource systems and resource units (as illustrated by green elements in Fig. 2). Most wild marine plants and animals (Table 1; RS1) are common-pool resources characterized by a high degree of rivalry and by difficulty of excluding others,⁹² though some marine species and ecosystems have distinctive characteristics (RU6) and clear boundaries (RS2) that facilitate exclusion. The abundance (RU5), economic value (RU4), and spatial and temporal distribution (RS3, RS9, and RU7) of marine resources all influence the likelihood of (un)sustainable use. Similarly, resource productivity (RS5) and robustness (depletability; RU2)—the ability of a resource to sustain itself in the face of human use (e.g., based on population growth rates)—differentiate marine species and ecosystems from each other.¹¹¹ Resource mobility (i.e., spatial movement of the resource, independent of user actions; RU1) and the capacity for storage (i.e., to capture and retain the resource for later use; RS8) are also key attributes that shape how humans govern and use marine resources.¹¹² Additional biological attributes of living marine resources (e.g., species, size, sex, age, and behavior) may shape how people interact with the marine environment and the impacts of these interactions.

MPA outcomes

Both theory and empirical evidence suggest that resource attributes, human resource-use patterns, and local context (discussed below) influence the ecological conditions (Table 1; O2) within and adjacent to an MPA. Common population-level

Table 3. Ecological domains, attributes, and illustrative indicators of the ecological impacts of marine protected areas (MPAs)^{113–115}

Domain	Attribute	Illustrative indicator
Population	Numeric density	Count of individuals per unit area
	Biomass	Abundance multiplied by mean weight
	Age structure	Frequency distributions of age classes
	Recruitment	Count of larvae per unit area
Community	Species richness	Number of species per survey
	Species diversity	Simpson diversity index
	Trophic structure	Distribution of trophic levels in species assemblage
	Functional redundancy	Number of species within functional groups
Ecosystem	Productivity	Fishery production
	Habitat characteristics	Extent
	Coastal processes	Sediment cycling
	Herbivory	Grazing rates

indicators of MPA ecological conditions include numeric density, biomass, and age and size structure of fish and invertebrates; ecological community-level indicators include species richness and diversity, trophic structure, and functional redundancy; and ecosystem-level attributes include habitat characteristics and key ecological processes (Table 3) (e.g., Refs. 113–115). In general, increases in these metrics suggest positive MPA impacts, although ecological dynamics associated with some “effective” MPAs may result in declines in some indicators (e.g., prey species decline following recovery of predators).^{116,117}

MPAs and other conservation interventions directly and indirectly influence human well-being through multiple pathways and mechanisms.^{89,118} By introducing new systems of marine resource governance, MPAs may enhance or reshape the flows of marine ecosystem services,^{22,119} including provisioning services (e.g., finfish and invertebrate fisheries); regulatory services (e.g., carbon sequestration); cultural services (e.g., tourism); and supporting services (e.g., biodiversity; Table 4).^{120–122} MPA governance regimes also define who may access these flows, reallocating the benefits of ecosystem services within and among social groups.^{47,123} Thus, MPAs shape the size of the marine resource pie (via ecosystem services) and determine who gets a slice of the pie (via property rights) and the size of the slice allocated to each individual (via property rights). In addition, the infrastructure and ideas associated with a conservation intervention may influence economic activities and social behavior, with direct and

indirect consequences for human well-being (e.g., Refs. 124 and 125).

The social impacts (Table 1; O1) of MPAs may be measured using diverse frameworks and indicators (e.g., UN Millennium Development Goals and UN Human Development Index).^{126,127} Each framework provides an alternative structure for characterizing human well-being, but they frequently share core constructs, such as economic well-being, health, security and political empowerment, education, and culture.^{22,43,128} Within each domain, indicators (Table 5) may be measured at one or more levels of social organization.¹²⁹ In Indonesia, for example, indices of material assets measure economic well-being at household,¹³⁰ settlement,¹³¹ and district levels.¹³² Measuring multiple dimensions of human well-being allows one to examine synergies, trade-offs, and equity among outcomes.^{123,133}

MPA impacts have ripple effects in space, time, and among outcomes (often referred to as “spillovers” or “leakage”; these impacts are both dynamic and complex, as studies of fishers have shown).^{57,63,134} For example, the redistribution of fishing effort from an MPA can increase the cost of fishing and lower profitability as a result of increased travel distance (and associated costs), increased exploratory fishing, and aggregation of fishing pressure in non-MPA locations.^{47,51,135} Observational studies^{34,35,86,136} and bioeconomic models^{137,138} indicate that stock recovery and ecological spillover (net emigration of adult biomass and larvae) from areas where fishing is

Table 4. Ecosystem service domains, attributes, and illustrative indicators of the ecosystem service impacts of marine protected areas (MPAs)^{120–122}

Domain	Attribute	Illustrative indicator
Provisioning	Fisheries	Fisheries catch
	Materials	Volume mined
Supporting	Biodiversity	Number of species
Regulatory	Carbon sequestration	Mangrove biomass
Cultural	Tourism	Annual value of tourism
	Recreation	Scuba diving annual value
	Existence values	Nonuse existence value

prohibited can result in increased fish abundance and catch per unit effort in fishable areas, thereby mitigating some or all of these costs. In addition to changes in fishing costs and catch, shifts in the catchability of target species and redistribution of fishing effort result in market feedbacks (e.g., prices, quantity demanded and supplied); fishers may subsequently adapt by changing their harvest strategies.^{44,51,57} Bioeconomic models and theory provide insights into these complex interactions and adaptive behavioral strategies, predicting how MPA economic impacts will vary over time and space (e.g., Refs. 63, 137, and 139). These spillovers influence research design, necessitating that studies address the manner in which these ripple effects may influence observations in non-MPA locations. If spillovers result in improved ecological conditions at a control site, for example, this will reduce differences in conditions inside and outside the MPA, resulting in a more conservative estimate of MPA impacts.²⁴ Establishing control sites at a distance beyond the expected influence of such spillovers allows for more reliable estimates of MPA impacts (see Ref. 70 and the case study described below).

Context

Elucidating the relationship between MPA interactions and outcomes requires controlling for contextual factors that may affect the likelihood of interventions or the nature of impacts. Marine resource governance (Fig. 1; GS), human activities (I), and ecological and social outcomes (O), for example, are shaped by the ecological (ECO) and social, economic, and political (S) context within which they are embedded.^{78,140} Context may manifest in a variety of ways, across a variety of scales, influencing the likelihood of a conser-

vation intervention occurring,¹⁸ its governance characteristics,¹⁴¹ and, ultimately, its social and ecological impacts.⁷⁰ Controlling for context—and other exogenous factors—allows one to measure the impact of an MPA by isolating the causal relationship between the intervention (i.e., MPA establishment) and its impacts (i.e., resultant changes in ecological and social conditions).

Biophysical context (ECO) has a substantive effect on marine resource governance, human behavior, and site-level social and ecological conditions. Conservation interventions are preferentially established in areas of high biological importance (e.g., high biodiversity or endemism)^{142,143} and low-opportunity costs of conservation (e.g., remote areas),^{144,145} with MPAs predominantly occurring in coastal areas¹⁴⁶—all illustrations of selection bias in the siting of MPAs. Biophysical context also structures historic and current human uses of the marine environment in and around MPAs; for example, upwelling areas of high productivity are often targeted by fishers, while high wave exposure can deter small-scale fishers.¹⁴⁷ Large-scale biophysical factors, such as temperature, productivity, habitat connectivity, and vulnerability to large storms, have shaped present-day ecosystems and continue to influence MPA ecological conditions.¹⁴⁸ Localized biophysical characteristics (e.g., wave exposure, depth, reef type, and benthic habitat characteristics) similarly influence the ecological community structure of MPAs and MPA responses to natural and anthropogenic disturbances—and conservation interventions.^{149,150} For example, the ecological recovery of corals within MPAs, which are associated with increases in herbivorous parrotfish, can be greater in sheltered areas where algae grow slowly.¹⁵¹ These biophysical characteristics may subsequently influence MPA impacts on human well-being, through ecological changes that have cascading effects on social conditions (e.g., ecosystem productivity may influence the intensity, duration, and yield of fishing efforts).

Social context (S) also shapes marine resource governance, human activities, and social and ecological impacts. Social structure influences the probability of collective action and self-governance, with decentralized governance structures more likely to emerge where the probability of local collective action is high.¹⁵² Traditions of customary marine tenure, for example, may foster local MPA

Table 5. Social domains, attributes, and illustrative indicators of the impacts of marine protected areas

Domain	Attribute	Illustrative indicator
Economic well-being	Occupation	Primary occupation
	Economic status	Household material assets index
		Trend in economic status
	Fishing characteristics	Primary fishing technique
Household dependence on marine protein		
Economic dependence on marine fisheries		
Health	Food security	Household food security index
		Child food security index
		Catch per unit effort
	Birth rate	Birth rate
		Adolescent birth rate
	Mortality	Infant mortality rate
		Under-five mortality rate
		Adult mortality rate
	Morbidity	Household disease rate
		Household disease burden
Political empowerment	Resource rights	Household marine tenure index
	Community organization	Participation in community groups
		Financial contribution to marine community groups
		Female participation in marine community groups
	Political engagement	Voting rates
Education	Formal education	Adult literacy rates
		School enrollment rates
	Environmental education	Awareness of threats to marine environment
Culture	Place attachment	Awareness of marine conservation actions
		Mean place attachment
	Social conflict	Trends in social conflict

Note: All indicators may be disaggregated by demographic characteristics (e.g., age, gender, wealth, education, and class) to explore the distributive impacts of MPAs.^{42,47,118,130}

establishment.⁶ At the same time, a lack of human capacity may limit the potential for MPA co-management or collaborative adaptive management.¹⁵³ National social context, by contrast, explains little variation in MPA abundance and spatial extent;¹⁸ for example, fishers per capita does not influence MPA establishment at the national level.¹⁸ Social structures (e.g., occupational structures and resource dependence) also shape MPA use rights and other aspects of marine resource governance.^{141,154} Differences in social systems (e.g., societal values and demographic trends (S2)) may also influence MPA impacts; social cohesion, for example, correlates positively with fisheries management outcomes.¹⁵⁵

Similarly, economic context influences marine resource governance, human activities, and ecological and social conditions. MPAs are often situated where opportunity costs for extractive uses are low,¹⁴⁵ creating considerable selection bias that

must be accounted for when comparing MPA to non-MPA locations.⁷⁰ Market access (Table 1, S5), for example, may influence MPA establishment and governance.¹⁴¹ Market access also influences resource use and ecological conditions, as well as human well-being in coastal settings;^{140,156,157} economic development has also been linked to fish biomass.¹⁵⁸ Market access may also influence the extent to which local communities depend on marine resources, which, in turn, may mediate the magnitude of MPA impacts on human well-being.^{42,63} For example, households with high dependence on marine resources are more likely to be affected by the reallocation of resource rights linked to MPA establishment.⁴² More broadly, the economic value of fishery resources has been shown to determine when and where fisheries develop¹⁵⁹ and whether overexploitation is likely to occur.¹⁶⁰ Fishing activity is heavily influenced by the opportunity costs of fishing (i.e., the next best

alternative income)⁶³ and economic incentives, where fishing costs (including distance) and expected returns (price, catch per unit effort) influence fishing locations, intensity, frequency, and gear choice.^{44,57}

Lastly, political context (S) may also shape marine resource governance, human activities, and social and ecological conditions.^{6,18,69,157} Country-level governance characteristics (e.g., political stability (S3), voice, and accountability) do not appear closely correlated with MPA establishment, though enabling legislation can accelerate MPA establishment (e.g., the Philippines),¹⁸ and shifts in marine resource governance may track the evolution of governance in postcolonial states.⁶ Decision-making arrangements may also influence MPA size and

location; scattered evidence suggests that decentralization policies foster many small coastal MPAs, whereas centralized decision making is associated with fewer, larger, and more remote MPAs.^{18,161} One might expect rule of law, corruption, accountability, and other contextual political factors to shape human behavior within MPAs—and MPA impacts—through macrolevel influences on fishing practices, tourism, or land use, but research has not yet examined these relationships fully (but see Ref. 162). The history of marine resource governance may shape ecological and social context and thus the probability of MPA establishment and/or the nature of MPA impacts, though rigorous research designs should control for such histories and other aspects of political context (for an example, see Box 1).

Box 1. 3FIGS in action: impact evaluation of MPAs in the Bird's Head Seascape, West Papua, Indonesia

In the Bird's Head Seascape (BHS) of West Papua, Indonesia, an interdisciplinary team^d is applying the 3FIGS approach to document and explain the social and ecological impacts of MPAs (Fig. 5).^{70,130} The BHS is recognized for its exceptional cultural and biological diversity, but human activities (e.g., destructive fishing practices and coastal sedimentation) have jeopardized both the ecological integrity of the region and the livelihoods of its resource-dependent residents.¹⁶³ Given these challenges, local and international organizations partnered to establish 12 MPAs within the BHS, encompassing more than 35,000 km². Through these MPAs, “empowered and capable Papuan communities, governments, and local partners protect their critical coastal and marine ecosystems, thereby protecting the single greatest reservoir of tropical marine species on the planet, while enhancing food security, livelihood opportunities, as well as their cultural heritage and traditional ownership rights.”¹⁶⁴ These MPAs, which include both multiple-use areas and no-fishing areas, establish preferential use rights for local residents that enable these residents to fish for subsistence and commercial use within the MPAs and empower them to exclude nonresidents ineligible to fish within the MPAs.

To determine the social and ecological impacts of the BHS MPAs and to test the null hypothesis of “no impact,” the scientific team employed a quasiexperimental impact evaluation informed by SESs to identify both outcome variables and potential confounders. To measure social impacts, the team first established baselines for eight MPAs and matched non-MPA controls. In addition to basic demographic information, household surveys documented human well-being (O1) using more than 150 indicators across five social domains: economic well-being, health, political empowerment, education, and culture. To identify non-MPA control households, the team used a multistep matching process at each MPA, designed to control for confounding processes (identified from the SES classificatory framework). An initial coarse match identified non-MPA settlements with key characteristics similar to MPA settlements. Drawing on the SES framework, coarse matching variables included occupation, social structure, market access, and political jurisdiction as proxies for the key attributes of context (S), resource systems (RS), resource units (RU), and actors (A) that may affect participation in an MPA or its outcomes. After the team surveyed these settlements (having used power analysis to determine the appropriate sample sizes for each settlement and each MPA in its entirety), it used Mahalanobis metric matching (a nearest-neighbor statistical matching method) to identify pairs of MPA and similar non-MPA households with similar observable characteristics. Statistical matching procedures, within an impact evaluation research

^dThe team is led by authors M.B. Mascia, H.E. Fox, L. Glew, and G. Ahmadia, as well as professor Fitryanti Pakiding of the University of Papua in Indonesia.

design, allowed the team to control for observable characteristics related to socioeconomic attributes (A2), ethnic composition (A6), and number of actors (A1) that could influence subgroup treatment effects (e.g., relative impacts on fisher versus nonfisher households). Baseline monitoring occurred in 2010–2012, following legal establishment of the MPAs and designation of boundaries, but before development of management plans and implementation of MPA zoning plans. To minimize the potential for spillover or leakage effects to bias estimates of MPA social impacts, control households and their fishing grounds were identified beyond known distances for economically meaningful levels of fish population spillover. Repeat data collection occurs at 2-year intervals until 4 years postbaseline, at which point monitoring will occur at 3-year intervals. The team uses difference-in-difference estimates of statistically matched MPA and non-MPA households to calculate the average treatment effect (i.e., impact) of each MPA for each of the social indicators. Demographic and spatial data allow the team to explore a targeted subset of spatial and temporal synergies, trade-offs, and equity within and among social groups and across domains of human well-being (O1), as well as to test hypotheses derived from theories of common-pool resource governance on the role of governance in shaping social impacts.

To monitor the ecological impacts of BHS MPAs, the scientific team adopted an analogous research design to measure changes in common reef ecosystem indicators (O2). Indicators included benthic (coral, other invertebrate and algal communities) and fish community attributes (e.g., abundance, size, and biomass of key reef species). After initially establishing ecological baselines within MPA boundaries (2009–2011), the team subsequently employed coarse matching methods to identify corresponding non-MPA controls (on the basis of 10 contextual variables describing structural, biophysical, and social features of coral reef sites (ECO, S))⁷⁰ and completed ecological baselines in control sites in 2012. Transect-to-transect statistical matching allows direct “apples-to-apples” comparisons of MPA and non-MPA coral reefs. Subsequent monitoring is occurring at 2-year intervals through baseline +4 years, at which point monitoring will occur at 2- to 3-year intervals. To reduce the risk of contaminated estimates of ecological impacts, control sites were sited beyond estimated distances for ecologically meaningful levels of fish population spillover.⁷⁰ As with social impacts, the team uses difference-in-difference estimates of changes in statistically matched MPA and non-MPA underwater transects to calculate the average treatment effect of each MPA across the ecological indicators. Life history and spatial data allow the team to explore a targeted subset of spatial and temporal synergies, trade-offs, and heterogeneities within and among ecological groups and across domains of ecological condition (O2). Larval dispersal and fish migratory behaviors can generate large-scale spillover effects, constraining the effectiveness of conventional use of fixed distance to minimize bias arising from interactions between intervention and nonintervention sites.⁷⁰ Consequently, estimates of MPA impact are interpreted with caution, particularly for highly mobile species.

To explain these social and ecological impacts and to test the null hypothesis that governance does not influence MPA outcomes, the team also monitors marine resource governance (decision-making arrangements (GS4), resource-use rights (GS5, GS6), monitoring and enforcement systems (GS8, I9, I10), and conflict-resolution mechanisms) in both MPA settlements and similar non-MPA controls.¹³⁰ Linked focus group discussions and key informant interviews provide data on key governance variables, allowing the team to test hypotheses derived from theories of common-pool resource governance. The team employs purposive sampling techniques to identify focus group participants and key informants in each settlement, given that knowledge of governance processes is not distributed uniformly or randomly among residents. Data collection among settlements occurs over two sampling periods; the data are pooled to estimate values for each governance variable at each time step. Governance data allow the team to explore the role of specific governance variables (GS) in shaping the direction, magnitude, and distribution of the social and ecological impacts of MPAs (O).

Discussion

Understanding what works, what does not, and why outcomes differ are fundamental challenges for conservation science and policy. A longstanding focus on ecological dynamics and human threats to biodiversity has led much of conservation to focus on what to conserve and where to do so.^{165,166} A proliferation of initiatives, employed

by government agencies and nongovernmental organizations, has emerged in response to these threats.² The limited scientific inquiry into the impacts of these initiatives—both to make sense of the world and to inform effective policy—has been plagued by a lack of social theory⁹¹ and by weak research designs that fail to control for alternate explanations of observed outcomes.¹¹

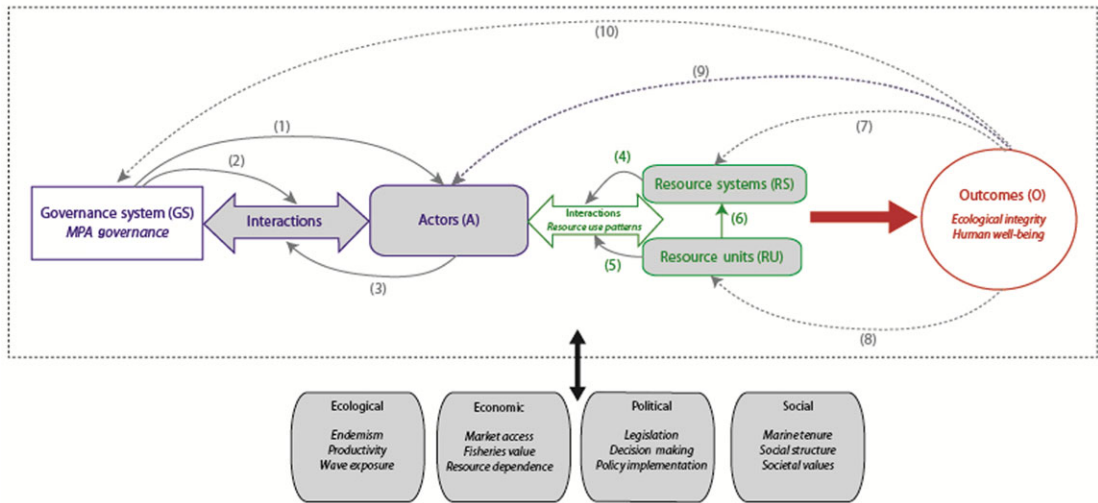


Figure 5. Application of the 3FIGS approach to understand the impacts of marine protected areas in the Bird’s Head Seascape, Indonesia. Conservation interventions often represent novel governance systems that induce a causal chain of events with intended and unintended consequences, feedback loops, synergies, and trade-offs. Related ecosystems (ECO) and social, economic, and political settings (S) in Figure 1 are collectively represented here as contextual variables. Solid lines represent direct links; dashed lines represent feedback mechanisms. Numbered arrows represent links labeled in Figure 1 as (1) “set rules for,” (2) “set conditions for,” (3) “participate in,” (4) “set conditions for,” (5) “are inputs to,” and (6) “are part of.” Numbered arrows (7–10) represent feedback mechanisms. Gray arrows and filled gray boxes represent elements of the social–ecological system that are explicitly controlled for through quasiexperimental research design.

The social impacts of conservation interventions remain particularly poorly understood.^{22,167} As a result, in many cases, conservation policymakers are shooting in the dark, not knowing which interventions work and which do not.^{11,168,169}

The 3FIGS approach provides a novel and robust means for documenting and explaining the intended and unintended impacts of MPAs and analogous biodiversity conservation interventions. Impact evaluations of terrestrial and freshwater protected areas, for example, could readily adopt the 3FIGS framework and adapt the MPA example to other biomes. Similarly, 3FIGS could be readily adapted for other place-based conservation interventions that focus on resource governance, such as forest and fisheries certification, payments for ecosystem services, and community-based natural resource management. For conservation interventions that focus on mechanisms other than governance (e.g., environmental education and economic reforms), the theoretical component of 3FIGS can be modified from common-pool resource governance to accommodate other social theories and associated hypotheses (e.g., theories

of planned behavior, commodity chains). Appropriate research designs, theories, and conceptual frameworks allow one to measure the direction, magnitude, and distribution of social and ecological impacts that emerge from conservation interventions, as well as the heterogeneity of these impacts among groups and across space and time. Examining MPAs and other conservation interventions as policy experiments provides the basis for both better understanding the world around us and designing more effective conservation interventions.^{11,170,171}

Caveats

Despite the power of a 3FIGS approach, however, integrating impact-evaluation research design, the SES conceptual framework, and hypotheses from common-pool resource governance theory is not a silver bullet for understanding the complex synergies and trade-offs that may emerge from MPAs and other conservation interventions. Furthermore, which interventions work and which do not may depend on the context, which is important for the interpretation and transferability to other contexts of impact evaluation results, which have high

internal validity but low external validity. Consequently, the practical application of the 3FIGs approach may be easiest where harvested species have limited mobility (minimizing spillover effects) and where an intervention affects a subset of the SES resource (creating a pool of viable control sites). The reductionist framework provided by impact evaluation imposes clear limits, both practical (e.g., complexity of sampling design)⁸² and analytic (e.g., subgroup treatment effects),^{172,173} on the scope of any given analysis; a reductionist approach may be insufficient to understand the full suite of feedbacks and interactions between social–ecological domains that are known to exist but remain poorly documented.¹⁷⁴ A classic example is “fishing the line,”¹⁷⁵ where an ecological response (i.e., higher fish abundance in the MPA spilling over beyond the boundary) drives a change in human behavior (i.e., spatial reallocation of fishing effort to the MPA boundary), which, in turn, may alter the ecological response (i.e., differential mortality rates alter fish behavior, lowering fish density close to MPA boundaries).¹⁷⁵ Similarly, identifying the unique contributions of factors that may covary with governance is a substantive challenge; for example, administrative activities and capacities, such as management plans, budgets, and staffing, have been hypothesized to shape impacts of MPAs and other conservation interventions,¹⁷⁶ but supporting evidence is weak.^{177–181} However, a recent study examining the relationship between management capacity and ecological performance of MPAs has shown that capacity gaps (e.g., budget and staffing) may explain the unrealized conservation potential of MPAs.²⁴

While novel analytical approaches (e.g., Ref. 89) increasingly enable researchers to explore complex causal mechanisms and interaction effects, minimum viable sample size¹⁸² and the danger inherent to multiple hypothesis testing¹⁸³ impose hard limits on model specification. In effect, the analytic constraints of impact evaluation will require scholars to choose between (1) “black box” approaches that are blind to the governance attributes of the intervention to capture emergent properties and feedbacks between outcomes and (2) carefully bounded analyses that explore the relationships among a subset of governance hypotheses and outcomes. Narrative or modeling approaches, buttressed by specific, testable

hypotheses, may be required to disentangle complex interactions.¹⁸⁴

Frontiers

Novel data-acquisition tools and analytic techniques may enable scholars to provide insights into increasingly complex questions about the impacts of MPAs. Crowd-sourced data and citizen science, for example, may provide an opportunity to build sufficiently large data sets to understand specific sets of emergent properties and interactions. Recent high-profile MPA research has benefited from widespread observations by nonscientist scuba divers;³⁸ marine citizen science has also been used to examine global population trends among manta rays.¹⁸⁵ Similarly, the increasing availability of government micro-data in online archives (e.g., the World Bank micro-data archives) will expand the geographic scope of global synthesis studies, including explorations of MPA social impacts. However, the emergence of Big Data alone will not be sufficient to provide empirical insights on 3FIGS. Bayesian statistical techniques that allow for the integration of qualitative data into quantitative models (e.g., as informative priors) and enhanced ability to document the uncertainty inherent to specific estimates may both broaden the suite of hypotheses that can be addressed in a single model and provide more nuanced insights into the emergent properties of SESs.

Some familiar challenges will likely remain, despite novel data-acquisition approaches and analytic advances. Data-synthesis efforts require more data than can be gathered by individual researchers or research projects, particularly for interdisciplinary analysis. Spatial or temporal overlap of ecological and social data-collection efforts is rare, and meaningful integration of multidisciplinary data sets poses both practical and theoretical challenges.²² MPA synthesis efforts based on published literature provide novel insights^{23,42} but are limited by methodological differences in underlying studies (which limit comparability). Synthetic analyses based on raw data are frequently constrained by the ability and willingness of researchers to share data and expertise. Research networks and standardized monitoring approaches provide a framework for data compilation and sharing while also addressing issues of data comparability. Forest- and development-focused research networks, for example, are generating

substantive insights on the role of governance in shaping the effectiveness of interventions (e.g., International Forestry Resources and Institutions; Jameel Poverty Action Lab (www.povertyactionlab.org)).¹⁰⁶

Conclusions

Despite the challenges associated with impact evaluation of conservation interventions, key scientific and policy advances are possible through a 3FIGS approach. In recent years, independent considerations of impact-evaluation research designs, hypotheses from common-pool resource governance theory, and the SES conceptual frameworks have provided novel insights into the performance of MPAs and other conservation interventions. Scientists now have the opportunity to build upon the strengths of these three approaches to generate fundamental insights into how the world works—the essential basis for evidence-based policy. The conservation community will never answer all of its questions, but greater conceptual clarity and analytic rigor will allow us to better understand how MPAs and other interventions shape society and the world around us.

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