Achieving the triple bottom line in the face of inherent trade-offs among social equity, economic return, and conservation

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Triple–bottom-line outcomes from resource management and conservation, where conservation goals and equity in social outcomes are maximized while overall costs are minimized, remain a highly sought-after ideal. However, despite widespread recognition of the importance that equitable distribution of benefits or costs across society can play in conservation success, little formal theory exists for how to explicitly incorporate equity into conservation planning and prioritization. Here, we develop that theory and implement it for three very different case studies in California (United States), Raja Ampat (Indonesia), and the wider Coral Triangle region (Southeast Asia). We show that equity tends to trade off nonlinearly with the potential to achieve conservation objectives, such that similar conservation outcomes can be possible with greater equity, to a point. However, these case studies also produce a range of trade-off typologies between equity and conservation, depending on how one defines and measures social equity, including direct (linear) and no trade-off. Important gaps remain in our understanding, most notably how equity influences probability of conservation success, in turn affecting the actual ability to achieve conservation objectives. Results here provide an important foundation for moving the science and practice of conservation planning—and broader spatial planning in general—toward more consistently achieving efficient, equitable, and effective outcomes.

marine protected areas | environmental justice | marine spatial planning | ecosystem-based management | social-ecological systems

Conservation and resource management require decisions about where, when, and how to allocate limited financial, human, social, and/or political capital resources (1). Whether designing protected areas, prioritizing restoration activities and locations, or limiting, promoting, or allocating certain uses of the landscape or seascape, the spatial and temporal distribution of management actions requires decisions about who may benefit and who may pay costs (2, 3). A large body of literature on conservation and spatial planning has been developed to help guide management strategies and decisions to be as efficient as possible at meeting stated goals (e.g., refs. 4–7). However, the goal of equitable distribution of costs or benefits across individuals or communities from use restrictions is rarely explicitly assessed in the planning process (8).

A fundamental tenet of conservation planning is that identifying optimal allocations of actions in space and time requires formulating the problem with explicit objective(s), constraints, potential actions, and system models that translate those actions into outcomes (1, 9). Objectives can take different forms, but the ultimate aim is to find the feasible set of actions that maximizes the value of those objectives (e.g., maximum gain in value, minimum area needed to achieve the objective). In most biodiversity conservation optimization problems, objectives are biological and framed as quantities, such as species viability or habitat representation, that are usually traded off against, or constrained by, economic outcomes. In the context of spatial planning and ecosystem-based management, objectives focus on particular services, but otherwise the problem formulation remains the same. In either case, economic outcomes are typically total cost (e.g., dollars spent) or opportunity cost (i.e., the monetary gains expected in the absence of conservation actions). Trade-offs can place in conflict those who prioritize economic versus biodiversity (or service) value (10); but in other cases, biodiversity conservation and economic value positively covary (e.g., ref. 6), such that strategic planning can deliver win–win solutions.

In many planning processes, there is awareness of social equity issues, where equity may be a function of, for example, equality of engagement in the planning process or reallocation of benefits or costs accrued under a management decision. In fact, achieving equity along with economic and environmental benefits—the "triple bottom line"—is commonly seen as the ideal outcome of conservation (11). However, rarely is equity incorporated into decision making in a formal way. Formalizing equity as a quantifiable and high-priority goal for conservation planning is feasible, as we discuss and demonstrate below. However, explicitly including this additional objective could compromise biodiversity conservation, or in other words create another potential trade-off among planning objectives (12).

Equity relates to how a person or group perceives the proportional availability of goods and services (e.g., is a given pool of resources evenly distributed and/or available?) or the relative deprivation compared with others (e.g., do others have more than I do?) (13). Despite the stated importance of equity in management and decision-making processes (e.g., ref. 14), there is no formal theory for addressing it in the conservation or spatial planning literature. Furthermore, perceived or real inequity can turn interested and cooperative participants into vocal opponents (15), leading to noncompliance or destructive actions (16, 17). Thus, equity can be a critical component of management and conservation success. Here, we explore the nature of potential

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trade-offs between equity and conservation objectives, test this theory in three case studies from around the world, and outline potential modifications to the theory that future empirical work could explore. Although our focus is on conservation planning, results are equally relevant to broader questions addressed within spatial planning contexts. Our work suggests that triple–bottom-line solutions to conservation are possible, but that such solutions depend on the form of equity being pursued. Importantly, including equity as an explicit planning objective leads to clearer delineation of trade-offs among multiple objectives.

Equity and Its Trade-Offs

Equity can manifest itself in a number of ways, with important implications for how it gets incorporated into conservation planning and the potential impacts it has on achieving conservation targets. There are two key dimensions to measuring equity: (*i*) what is measured, which can include monetary loss or gain, access to resources gained or lost, and level of participation in a process (18), and (*ii*) how it is measured, either in absolute or relative terms. The former defines the metric(s) used to assess equity; the latter determines how groups are compared with each other. The metrics used essentially link to three classes of problems in conservation prioritization: economic benefits such as money or rights to use resources are being distributed among a suite of political entities (e.g., countries, states, regions, nongovernment organizations, or local governments) (19); conservation actions, such as reserves or restrictions on uses, are being put in place that are believed to impact or benefit a variety of communities or industries (20); and voice or opportunity is given to different groups in a deliberate process (e.g., stakeholder involvement or gender equity) (e.g., refs. 21, 22). Here, we empirically explore the first two problem types, but acknowledge that participatory equity may be more important for achieving desired outcomes than the other types of equity in some cases.

Once the type of equity to be measured is defined, the target objective for equity can be set in a number of ways. To date, most policy has focused on avoiding extreme cases of inequity, in particular those producing unethical conditions, within a framework of environmental justice (e.g., refs. 23, 24). More recently, attention has also focused on optimizing social equity through instances where all stakeholders are included in the planning process (18) or are affected equally by actions (12, 25, 26), and to a lesser extent through consideration of intergenerational equity (27, 28). It is typically assumed that increased equity comes at the cost of financially optimal conservation solutions, but the nature and shape of that trade-off is generally unknown (29). In theory, the trade-off could take any potential shape (Fig. S1), as is seen with trade-offs among ecosystem services (10, 30). Through three case study assessments, we evaluate the shape of these trade-off curves and explore the implications of such trade-offs for achieving conservation objectives.

Case Studies

Our three case studies include the following: (*i*) the central coast of California (United States), where a network of marine protected areas (MPAs) was recently created with consideration of impacts on local fisheries, (*ii*) an MPA in the southern Raja Ampat region of Indonesia where proposed no-take zones may differentially impact villages' fishing access; and (*iii*) the Coral Triangle region where international aid money is being distributed among six countries to mitigate threats to their marine resources. As such, these cases evaluate two different metrics of equity—dollars and access—and for the Coral Triangle example in particular we explore implications of considering absolute versus relative (i.e., proportional) changes in equity.

California Marine Protected Areas. California recently completed an extensive, 8-y planning process to design and implement a network of MPAs in its state waters, initiated by the Marine Life Protection Act (MLPA) (31). Synthesis of existing information and development of new analytical frameworks provided a vast array of information on the potential trade-offs between conservation and fisheries values under different MPA network designs (32, 33). We focus here on the central California region within the MLPA process (Fig. S2*A*), because data for the area are published and available (26). Previous analyses for this region focused on the trade-off between how well conservation objectives were met within a given MPA network and the potential total costs to fisheries (7). Here, we focus on implementing marine reserves only (the MLPA process included less restrictive MPAs as well) and define equity as cost in dollars to eight separate commercial fisheries, and measure equity using the Gini coefficient [defined as the dissimilarity in costs or benefits among different entities (*Materials and Methods*)]. We explore how different overall budget constraints on the combined value lost by fisheries interact with equity to influence the nature of the trade-off between conservation goals and equitable fisheries impact.

Given budgets set to 3–20% of total fisheries value, equity traded off nonlinearly (concavely) with the degree to which conservation goals could be achieved for all budgets (Fig. 1*A*). Greater levels of both equity and conservation goals could be achieved with higher total budgets (Fig. 1*A*). The points in Fig. 1 approximate the "efficiency frontier" where optimal solutions lie, and represent different importance (weight) given to conservation versus equity goals under each budget scenario. The absence of solutions with equity less than 0.6 suggests that it is possible to avoid highly uneven impacts on fisheries under any budget scenario; given the budgets considered here (≤20% of the total value of fisheries), any reserve network solution still leaves substantial area open to each fishery. The nonlinear shape in the trade-off curves shows that substantial increases in achieving conservation goals can be achieved with minimal cost to equity, and vice versa, especially for higher budgets. The result that higher total budget increases equity emerges from the increased flexibility to "impact" higher value fisheries (with a small total budget, total impact is less, but one or a few fisheries experience the brunt of it). As expected, greater total budget allows for greater conservation outcomes for a given level of equity (7).

We also found that when conservation goals were prioritized at a low level relative to equity (i.e., weighted less than ∼10% in the objective equation in *Materials and Methods*), solutions all

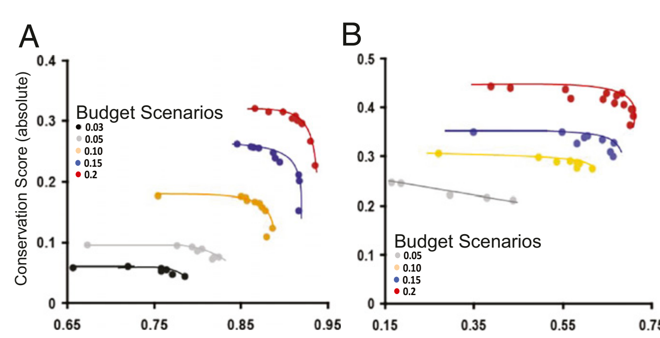

Fig. 1. Trade-offs between achieving conservation goals and equity, measured under the following budget scenarios: (*A*) monetary impact to the fishing industry in central California with different budget constraints in place or (*B*) loss of fishing grounds in the Misool region of Raja Ampat, Indonesia. In both cases, the plots represent absolute measures of conservation objectives. The outer edge of the points is drawn to approximate the efficiency frontier; points interior to this frontier resulted from simulations but are suboptimal.

converged on perfect equity plans without marine reserves (i.e., no conservation gain but also no cost to any fishery; result not shown in Fig. 1). Solutions exist with modest conservation and high equity outcomes (Fig. S3), but the trade-off with equity (when equity is weighted highly, >90%) makes these solutions too costly, because much greater overall value of combined objectives can be achieved with the no-reserve solution. Using smaller (i.e., higher resolution) planning units could resolve this issue by creating more planning options and thus greater flexibility. However, our results here are realistic because our resolution mirrors what was used in the actual planning process and is practical for most situations.

Southeast Misool Marine Protected Area. There is an ongoing process to zone a network of multiuse MPAs in Raja Ampat in eastern Indonesia to support biodiversity conservation and sustainable fisheries (12). We focus here on Southeast Misool MPA (Fig. S2*B*). Thirty villages have customary marine tenure and rights to the MPA, which governs where each village can fish. The tenure system in eastern Indonesia is complex, such that declaring a no-take marine reserve within the larger MPA affects different individuals, families, clans, or villages. We simulated different no-take reserve network designs and assessed their performance in representatively protecting different types of coral reef habitat (and mitigating stressors to locations) and affecting equity across villages in lost fishing grounds. We varied a constraint on the maximum area in no-take reserves as a proxy for different conservation budgets for the creation of marine reserves.

Trade-offs were direct (close to linear) when total (area) budgets were small (<10% of total area within the MPA placed in marine reserves; Fig. 1*B*) and became weaker (concave) with larger budgets. The concave shape suggests that initial gains in conservation objectives or equity can be achieved with minimal cost to the equity objective. When assessed as proportional rather than absolute differences in how well conservation objectives were achieved, most trade-off curves were nonlinear (Fig. S4).

Interestingly, the point at which equity overrides conservation objectives, forcing solutions to the zero-reserve outcome, is when equity is prioritized only slightly more than conservation (i.e., weighted >60–75%), rather than 90% as in the California example (Fig. S5). This difference emerges because solutions with reserves had lower equity scores in Southeast Misool than California, due to the fact that about one-half of the coral reef habitat features in the Misool MPA occurred in fewer than 20% of the fishing grounds. These sites are critical to achieving overall conservation objectives, causing greater inequity to villages that fish those sites. This uneven distribution of key habitats therefore requires higher weighting on conservation versus equity objectives to overcome this effect. As with the California example, higher resolution planning units would likely allow for solutions with higher equity targets, but such small planning units are generally not feasible for implementation or enforcement. Habitats restricted to a few fishing grounds also cause a much larger range of equity values for conservation solutions on the frontier in the Indonesia example than is seen in the California example.

Coral Triangle. The Coral Triangle is composed of six countries (Indonesia, Philippines, Malaysia, Timor Leste, Solomon Islands, and Papua New Guinea), divided into 16 ecoregions (Fig. S2*C*), whose waters contain the highest global coral biodiversity, but also some of the most threatened systems (34). The multilateral Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (formalized in May 2009) is the focus of significant global conservation attention with financial commitments of at least US$400 million (www.coraltriangleinitiative.org).

Previous work explored the costs and benefits of investing in land versus marine conservation to help guide the distribution of financial resources (35). Here, we expand this analysis and explore two types of equity, the distribution of funds (total and per capita) to each ecoregion and the costs from restricted access due to MPA creation per ecoregion. We evaluated how the type of equity affects conservation outcomes for the Coral Triangle, measured as the reduction in total fishing impact to reefs across the Coral Triangle region. As such, this case study allows exploration of two metrics of equity (access and money) and both methods of assessment (absolute and proportional). Furthermore, we explore how decisions about whether to initially allocate portions of the total budget (or area set aside in marine reserves) equitably versus cost effectively influences outcomes. The difference reflects that budgets can be split between different objectives (e.g., budget allocated each to equity and cost effectiveness objectives), with the order in which this is done potentially affecting results. Such decisions are likely common to almost any planning process.

For the two scenarios that allocate low-to-moderate amounts of money to ecoregions (US$80 and US$160 million), there is a nearly direct trade-off between equitable distribution and the ability to achieve conservation objectives (i.e., mitigate fishing impacts; Fig. 2*A*). For very high total budgets, the trade-off curve becomes concave. This nonlinearity emerges because when more than ∼60% of funding is allocated equitably, entire ecoregions receive sufficient funding to fully meet conservation objectives before the total budget is spent for that region (and it is not reallocated to other regions). Thus, this nonlinearity is due in part to the coarse scale of planning units; nonlinearity in the California example instead emerged from underlying biophysical properties of the system. Nearly identical results emerge when measuring equity as per-capita allocation of funds (Fig. 2*B*). A notable exception is the unexpected results for equitable-first allocations at 75% and 80%—these two solutions have lower equity than solutions that allocated less equitably first (65% and 70%) because the smallest, least populated ecoregion contains

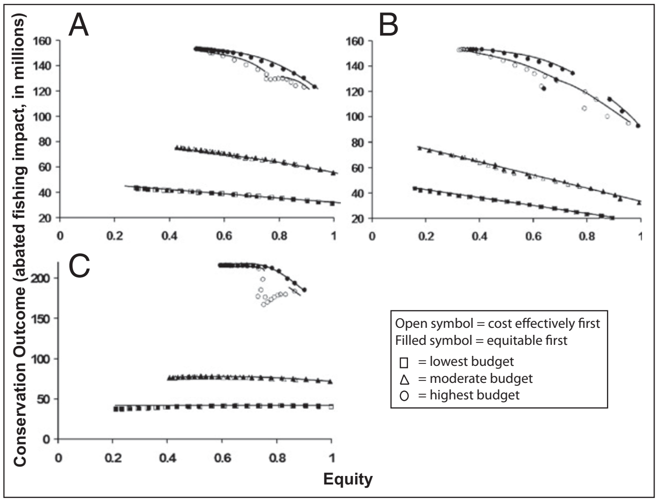

Fig. 2. Trade-off between measures of conservation impact (mitigated fishing pressure) and the equity of distribution of that impact across ecoregions in the Coral Triangle region for (*A*) total budget, (*B*) regional per-capita budget, and (*C*) total area protected. The open symbols represent allocations that were done first cost effectively, and then equitably; the closed symbols are the reverse. Each point represent 5% additional amount distributed cost effectively or equitably first, respectively. In *A* and *B*, total budget is US$80 million, US$160 million, and US$650 million. In *C*, total area set aside is 2,801 million, 5,602 million, or 22,408 million km^2, representing 5%, 10%, and 40% of the total region, respectively. The outer edge of the points is drawn to approximate the efficiency frontier; points interior to this frontier resulted from simulations but are suboptimal.

relatively cost-effective sites and, when resources are allocated at least 30% cost effectively, the entire region receives protection. Once that proportion drops to 25%, resources are freed for allocation to other ecoregions, increasing inequity across ecoregions. These solutions are far inside the efficiency frontier and so should never be selected, i.e., one could achieve the same amount of equity but much higher conservation outcome with lower amounts of funds allocated first equitably (Fig. 2*B*).

Surprisingly, there is no trade-off when equity is instead measured as area within marine reserves (i.e., reduced access) for low and medium amounts of total area protected, such that one should always strive for perfect equity in these cases because one can achieve the same conservation outcome at all levels of equity (Fig. 2*C*). This result emerges because when equity in area across ecoregions is ignored, the most cost-effective sites are selected for protection, resulting in several ecoregions receiving almost no protected areas (Table S1). Instead, when emphasis is placed on achieving equity, a portion of each ecoregion must be protected. In some cases, these protected places mitigate more threat than in the more cost-effective scenarios, even though they are not cost effective, i.e., considerably more expensive to mitigate equivalent amounts of threat. In this particular example, the trade-off between cost effectiveness and equity led to nearly identical conservation outcomes; it seems unlikely that this would hold in other cases.

Two additional key results emerge from this case study. First, for low and moderate budgets, there is essentially no difference if one first allocates funds (or area) equitably and then selects locations that cost effectively meet conservation objectives, or vice versa. This result does not imply that no trade-off exists between objectives—higher equity comes at the direct, linear cost to conservation—but it does mean that for any given level of equity, one can allocate funds equitably first and still achieve the same conservation outcomes.

Second, for very large budgets, the trade-off becomes nonlinear, as noted above, but in ways that differ for approaches that allocate resources first equitably versus cost effectively. "Cost-effective–first" solutions mitigate less threat than "equitable-first" solutions. This result emerges because equitable-first solutions require area within each ecoregion to be protected, even if those areas are not the most cost effective over the entire region; they reduce more threat, but at higher cost. We do not see this result for lower total budgets because no ecoregion is receiving sufficient funds to protect the whole area under these budgets, so both equitable-first and cost-effective–first solutions select similar, cost-effective sites for protection. Furthermore, for the highest total area budget (Fig. 2*C*), the equitable-first approach produces the typical concave trade-off curve, whereas the cost-effective–first approach produces a split curve, with the initial half showing the typical concave trade-off, whereas the second half shows a strong positive relationship. These solutions interior to the frontier are inferior and should not be chosen, such that one would always favor the full-equity solution in this latter region of the curve and the low-equity, high-conservation solutions in the early region of the curve (Fig. 2*C*). This split-curve result emerges because cost-effective–first approaches will select the best sites across the whole region first, leading to all sites within small ecoregions being selected once equity reaches about 0.75; as equity increases beyond this, more expensive high-value sites in other regions get selected, causing the conservation outcome to increase. The relative size of each region and the distribution of conservation targets within those regions should have a strong influence on the presence and shape of this split curve. The split curve is not seen when allocation is done equitably first because the priority is to have protected areas spread among regions, making it less likely that entire ecoregions will be protected under any given budget.

These stark differences in the nature and shape of the trade-off between equity and conservation objectives when using different metrics (monetary cost versus access to areas) and methods (absolute versus per capita) highlight the critical importance of defining which metrics of equity and methods for assessing it matter most to people engaged in, or affected by, a planning process. The set of optimal solutions will vary greatly under these different approaches to incorporating equity, and management focus on an inappropriate metric could significantly decrease the probability of success of a proposed solution.

Equity and the Probability of Success

The above analyses and discussion do not address an important aspect of equity that may allow for combination of the two currencies into a single measure of triple–bottom-line outcomes. Highly inequitable solutions are more likely to fail because those who are disenfranchised from the benefits or outcomes of the process often feel little motivation to adhere to the agreement (15). Increases in equity are typically believed to improve the probability of success by increasing likelihood of self-enforcement of new regulations because people perceive the regulations as fair (36, 37), yet it is equally likely that management will fail if the needs or desires of particularly vocal or powerful minorities are not met. Most of these assumptions remain untested.

Here, we simulate the consequences to conservation prioritization of considering both social equity and its impact on the probability that a plan is enacted or upheld. Empirical assessment of these interactions would require a large sample of conservation actions where equity and conservation effectiveness are measured, information that currently does not exist and a field of research that merits significant attention. For now, we assume probability of success increases asymptotically with increasing equity, and that extremely inequitable solutions have near-zero probability of success and that the best case scenario has very high but not guaranteed chance of success (*Materials and Methods*). If instead probability of success peaked at mid-levels of equity, for example if powerful stakeholders influence the outcome, then our results would be even more pronounced.

We assume that expected conservation success is the product of the probability of success and the biodiversity outcome given particular levels of equity. Simulations using simple assumptions about the relationship between social equity and probability of success show a clear peak in achieving conservation objectives with modest levels of equity (Fig. 3). This result is striking in that it highlights how final conservation outcomes could be made much more durable with even modest consideration of equity effects, by avoiding inequitable outcomes that have little probability of success, but also better achieve desired outcomes by avoiding high-equity solutions that excessively compromise conservation objectives. In other words, the low probability of success when equity is low erases nearly all potential conservation benefit, whereas the cost to conservation objectives with very high equity offsets the value added from increased probability of success (Fig. 3). These results may seem intuitive, but the framework developed here provides a tool for quantifying these interactions and helping to optimize decision-making outcomes. Effort early in the planning process to engage and elicit stakeholder preferences for different dimensions of equity would significantly improve our understanding of what the probability of success curve actually looks like. In fact, research has shown that participatory processes that do not engage those with significant stakes in the outcome of the decision (but often little voice) are less likely to address equity issues (e.g., ref. 21).

Discussion

The spatial patterns of underlying mechanisms that produce conservation objectives (species distributions, spatial patterns of threat, and costs to mitigate those threats, etc.) generally require

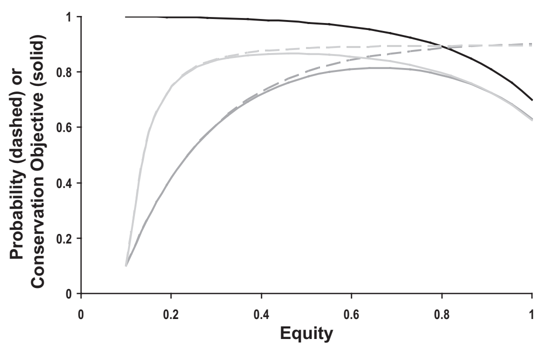

Fig. 3. The relationship between equity and biodiversity, and how probability of success given different levels of equity modifies the ability to achieve biodiversity conservation targets. the solid black line shows the trade-off between conservation objectives and equity. The dashed gray lines show two hypothetical shapes for the relationship between equity and probability of success, and the solid gray lines are the resulting consequences of these probability curves on the degree to which conservation objectives are met.

inequitable distribution of resources to achieve optimal conservation outcomes. However, few planning processes focus solely on achieving conservation objectives, given stakeholder interest in minimizing negative impact to specific groups or maximizing economic gain. This tension among values sits at the heart of perceived and real trade-offs among conservation objectives, total economic gains (or losses), and social equity. To date, the issue of equity has largely been addressed indirectly, through implicit assumptions about spreading costs or benefits, or as a secondary concern, as with post hoc comparisons of the equity of outcomes (36). We have shown here that explicit assessment of how equity influences the ability to achieve conservation outcomes produces a more nuanced and realistic picture of the effects of any given conservation objective on different groups, and may indicate under what conditions significant trade-offs are likely to occur. Hopefully, applying this framework will lead to solutions unrecognized without direct consideration of equity.

The solutions that lie along the "frontier" in the case studies are triple–bottom-line solutions, where one can optimize conservation goals and equity while minimizing costs. Solutions interior to these frontier solutions (most of which are not plotted) are all possible and represent the many ways decision making can miss the mark on the triple bottom line. As in other trade-off assessments (5, 6, 30), finding the frontier does not then prescribe a single correct solution but instead presents the range of options, all optimal, that represent the trade-off between stated goals. As the case studies show, there is almost always a trade-off between biodiversity conservation and equity, but the extent of this trade-off varies depending on the context and the exact formulation of the objective function. Ignoring issues of equity in conservation planning will likely produce suboptimal outcomes and risks failure in prioritization efforts and durability of implemented actions.

We have focused here on a few types of equity, namely the distribution of costs and access to resources. Although these two types are likely the most common to conservation planning exercises, many other types clearly exist, most notably gender (16, 17), intergenerational (22, 23), and geographic equity [such as with global trade and its displacement of environmental impacts, and the corollary, climate change impacts (38)]. These different kinds of social and economic equity likely constrain conservation prioritization and planning in different ways, yet to be explored formally.

Two key assumptions affect our results and suggest important areas for further research. First, we measured biodiversity objectives by tracking how much threat was abated in a given location. This is a proxy at best for true changes in conservation values and outcomes, and so the actual shape of the trade-off between equity and conservation objectives may differ from what we found here. Perhaps more importantly, threat abatement can be achieved more quickly than ultimate conservation goals, such as number of species recovered to stable population sizes. Because the consequences of social equity play out relatively quickly whereas conservation goals tend to take time to achieve, full treatment of equity issues in conservation planning need to address the temporal as well as spatial components. Second, the shape of equity-probability curves characterizing how equity affects the likelihood of success of a plan remains largely unknown. Empirical research focused on determining the shape of this curve would provide the key to combining the two currencies into a single metric, allowing for more accurate identification of triple–bottom-line solutions.

Conservation planning, whether in the ocean or on land, strives to find optimal solutions in the face of inherent constraints. Triple–bottom-line outcomes remain highly prized, but they cannot be achieved regularly without formal approaches to considering equity alongside the more traditional focus on minimizing costs and maximizing conservation objectives. Incorporating equity can produce nonintuitive results, as with the California and Raja Ampat case studies where strong emphasis on equity leads to zero-MPA solutions. More importantly, it produces realistic results, and that realism will go a long way toward building stakeholder acceptance of management plans and outcomes.

We have focused here on marine conservation planning problems, but the approach and implications of the results are relevant to a broader spatial planning context, where planning objectives can include ecosystem services other than biodiversity conservation. Social and economic equity is almost always on the minds of stakeholders involved in these processes; the framework and theory we have developed here provides a means to make such concerns explicit and quantitative.

Materials and Methods

In each case study, we implemented marine reserves (i.e., no-take areas) and assumed that their implementation eliminates fishing from the reserve region and that the fishing is not redistributed. The conservation benefit of reserves varied across case studies, described below and in *SI Text*. Although the type of equity measured in each case study was different, we use the same metric to evaluate equity, the widely recognized and used Gini coefficient (39). In our context here, the Gini coefficient measures the dissimilarity in costs or profits among different entities. It indicates the difference between a perfectly equitable distribution and the actual distribution of a resource. Although the Gini coefficient is commonly used as a measure of inequality of wealth (40), it has also been applied to describe other types of inequalities (41–44). We adapt the Gini coefficient to measure equality rather than inequality by using its inverse (1 − Gini, henceforth referred to as "equity"), where a value of 1 represents perfect equality and a value of zero represents maximal inequality (Eq. **S1**). Details for data used in each case study are provided in *SI Text*.

California and Raja Ampat Case Studies. For the California and Raja Ampat case studies, we examined the trade-off between conservation and equity goals constrained by a fixed budget. The budget was defined as the total monetary cost to fisheries and the total area lost within fishing grounds, respectively. For California, we present trade-off curves with the budget ranging from 3% to 20% of the combined value of fisheries. Optimal solutions on the trade-off frontier were searched for using the objective function Obj = max $[\alpha E_1 \mu + (1 - \alpha)E_2]$, subject to the budget constraint $\Sigma(C_k) \leq B$, where α is the conservation weighting, E_1 is the equity in habitat representation in reserves, E_2 is the equity in fishery impacts of reserves, and μ is the minimum representation of a habitat in reserves (Eq. **S1**; see Table S2 for parameters used to calculate E). Thus, a reserve plan with either low representation equity or low representation of a single habitat would have a low conservation score. C_k is the costs to each fishery of the reserves and B is the total budget (e.g., see ref. 45). Varying the conservation weighting 0–1 gives the optimal solution for different points on the trade-off frontier. The set of possible reserves is too large to explore exhaustively (2^{3610} possibilities in CA and 2^{670} in RA), so we used simulated annealing to find near-optimal solutions (46, 47). For all annealing simulations, we compared the objective function value for the

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near-optimal solution to its value with no marine reserves, setting $\mu = 0$ and $E_2 = 1$. Although true optimal solutions cannot be found without an exhaustive search, the performance of the optimization algorithm was checked by comparing its results to outcomes from 1 million randomly sampled marine reserve plans for each case study. The frontier found using simulated annealing was considerably better than random.

Coral Triangle Case Study. We used the Coral Triangle boundaries and ecoregions ($n = 16$) defined by Veron et al. (48) on the basis of coral diversity and endemism. We used the global coral reef atlas (49) to determine the presence/absence of coral reefs for each 1-km^2 cell in each ecoregion. The objective of this case study was to minimize fishing impacts on coral reefs through investment in marine reserves, given a fixed budget that could be used to compensate for changes in economic opportunity arising from given actions, such as for lost fishing opportunity. To determine the priority of an area for designation as a marine protected area, we calculated return on investment of protecting each 1-km^2 reef unit, where return was measured as reduction of fishing and investment as cost of reducing each threat. Using this information, we allocated resources using two different methods: (*i*) "cost-effective" allocation, where resources are allocated to coral reefs with the highest return on investment; (*ii*) "equitable" allocation, where resources are divided equitably between each of the 16 ecoregions, and then allocated cost effectively within each ecoregion and visa versa. We analyzed the trade-off between conservation (i.e., reduction of fishing pressure) and equity (i.e., distribution of resources to ecoregions) for scenarios that range from spending 100% of the budget cost effectively for conservation to 100% equitably for the community. We implemented different types of budget constraints: (*i*) financial budget of \$80 million, \$160 million, and \$650 million; (*ii*) financial budget per capita, such that, when allocated equitably, is split equally among people; and (*iii*) area budget of protecting 2,801, 5,602, and 22,408 km^2 of coral reef (5%, 10%, and 40% of the total region, respectively). Financial budget constraints were based on a value that, when distributed equitably, was insufficient to protect any ecoregion entirely (US\$160 million), and one-half and four times that amount (for illustrative purposes). Area budget constraints were based on a 10% target (5,602 km^2), a common target for protection, and equivalent one-half and four times changes as with the monetary budget.

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