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Self-financed marine protected areas

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Abstract

Marine protected areas (MPAs) are an important tool for conservation but can be victims of their own success—higher fish biomass within MPAs create incentives to poach. This insight underpins the finding that fishing persists in most MPAs worldwide, and it raises questions about MPA monitoring and enforcement. We propose a novel institution to enhance MPA design—a ‘Conservation Finance Area (CFA)’—that utilizes leased fishing zones inside of MPAs, fed by spillover, to finance monitoring and enforcement and achieve greater conservation success. Using a bioeconomic model we show that CFAs can fully finance enforcement, deter illegal fishing, and ultimately maximize fish biomass. Moreover, we show that unless a large, exogenous, and perpetual enforcement budget is available, implementing a CFA in a no-take MPA would always result in higher biomass than without. We also explore real-world enabling conditions, providing a plausible funding pathway to improve outcomes for existing and future MPAs.

1. Introduction

Marine protected areas (MPAs) cover 7.7% of ocean area (Marine Conservation Institute 2020), with global targets to expand this to 30% by 2030. When properly designed and enforced, MPAs have proven to be robust and adaptive tools to protect marine resources (Lester *et al* 2009, Gaines *et al* 2010, Edgar *et al* 2014), while providing social, ecological, and economic benefits (Lester *et al* 2009, Roberts *et al* 2017). However, many MPAs fail to achieve their objectives, often due to insufficient and underfunded monitoring and enforcement (Edgar *et al* 2014, Gill *et al* 2017). Poaching inside MPAs is a primary cause of their failure to produce conservation benefits (Rife *et al* 2013, Bergseth *et al* 2015, 2018). Higher fish biomass inside an MPA creates incentives to poach, setting up underenforced MPAs to potentially become victims of their own success. Paradoxically, effective MPA enforcement may beget a need for more enforcement—and greater resource demands—to keep poachers at bay.

Science supporting the purpose, design, and execution of MPAs has evolved to help overcome previous shortcomings related to monitoring, enforcement, and compliance. Past innovations include creating multi-use areas to reduce user conflict, community-based conservation to gain stakeholder buy-in, and incorporating new technologies, including satellite-based remote sensing and electronic monitoring (Game *et al* 2009, Recio-Blanco *et al* 2019). Such changes have allowed MPAs to remain a flexible and efficient institution in the conservation toolkit. These innovations notwithstanding, most of the world’s MPAs experience persistent poaching (Bergseth 2018), with relatively few solutions yet identified.

Biodiversity benefits within MPA borders are well documented (Lester *et al* 2009), as are the benefits to local fisheries through the spillover of fish as either adults or larvae to adjacent fished areas (e.g. Krueck *et al* 2017). Both theory and empirical work demonstrate that properly designed and monitored no-take zones can enhance biomass in adjacent fishing areas through spillover (Nowlis and Roberts 1999, Pezzey *et al* 2000, Rodwell *et al* 2002, Gaines *et al* 2010, Lenihan *et al* 2021). Here, we leverage spillover benefits from no-take reserves to motivate a novel MPA design feature—which we define as a 'Conservation Finance Area' (CFA)—to help overcome the challenges of adequate enforcement by providing a financing pathway that is economically sustainable. A CFA would be a designated area around a no-take zone where fishing vessels can lease exclusive fishing rights (figure 1), with the proceeds of leasing used to finance MPA enforcement. Higher fish biomass inside a well-enforced no-take area creates the demand for leases via spillover, a demand that is not produced in poorly enforced or designed MPAs due to the lack of biomass build-up and subsequent spillover.

CFAs would represent a novel application of user-fee models for public-goods provisioning, but user-fee models exist in many other contexts. Existing user-fee examples include financing highways via tolls, public universities through tuition fees, and national parks through entrance fees. Within the conservation context, game reserves collect sizable access fees in exchange for special hunting opportunities in areas of high diversity and abundance (van der Duim *et al* 2015). The marine tourism sector has also had some success financing MPA operations through entrance fees collected in exchange for access to high quality recreation sites (Dharmaratne *et al* 2000, Depondt and Green 2006, Thur 2010, Gelcich *et al* 2013). The viability of conservation access fee programs hinges on their ability to provide users access to sites that are both desirable and accessible (Spergel 2001). In ideal settings fees are set to capture users' willingness to pay and supply the funding needed to maintain the desired conservation outcomes.

We explore the potential of CFAs to sustainably finance MPA enforcement in several ways, allowing for the possibility that they may not be an optimal solution. We start from the premise that a manager wants to implement an MPA with the goal of maximizing system-wide fish biomass, or another conservation objective correlated with this outcome. First, we use numerical simulations to assess the effects of CFAs on fish biomass, as well as to explore how the optimal design of a CFA depends on the biological and economic characteristics of the system. We then derive the CFA size that optimizes the conservation outcome, and show that the optimal CFA size is always greater than zero in the absence of an exogenous enforcement budget large enough to deter illegal fishing. The intuition of this finding is that an MPA with no enforcement has no benefits (a 'paper park'), and thus creating a CFA to fund enforcement improves conservation outcomes, despite the fishing the CFA allows. This finding provides a proof of concept for our proposed institution, which we further reinforce with analytical proofs (see supplementary information, SI, available online at stacks.iop.org/ERL/16/125001/mmedia). Ultimately, we demonstrate that a CFA can be a powerful policy tool to enhance the success of existing MPAs, and to support the creation and enforcement of new—and importantly, effective—MPAs.

2. A market-based design strategy for MPA financing

Our model considers a marine area divided into two patches: an MPA, M, and an open-access fishing area, F (figure 1). We ask: how can the MPA be managed to maximize the system-wide conservation outcome? Standard MPA design would designate the entire MPA as a no-take reserve. If monitoring and enforcement were perfect, this solution would indeed maximize the conservation outcome (Sala and Giakoumi 2018, Turnbull *et al* 2021). However, the incentive to poach undermines MPA efficacy and conservation outcomes when enforcement is costly and the MPA lacks a large perpetual enforcement budget.

An alternative approach is to zone the MPA to allow for different uses in different areas (Klein *et al* 2010). We explore a zoning scheme that divides the MPA into two areas: a no-take zone where all extractive activities are prohibited and human use is regulated, and a CFA where fishing effort is strictly controlled and managed for sustainability. In the fraction L of the MPA designated as a CFA, fishers must pay a per-unit effort access fee (alternatively, the fee could be levied per-unit harvest) to fish. The remaining fraction of the MPA $(1-L)$ does not allow fishing.

We assume the amount of poaching is endogenously determined by economic incentives: fishers will balance the profitability of fishing inside the MPA against the expected fine for fishing illegally. Poachers face a probability of being caught—determined by the level of enforcement—and an associated penalty (here a fine). With no enforcement budget, the MPA becomes a 'paper park'; with an infinite enforcement budget, all illegal fishing can be perfectly deterred. Reality often lies in between: a modest enforcement budget is available, which deters some, but not all, illegal fishing. Under our CFA model, the lease revenue generated from the CFA supplements any existing exogenous enforcement budget, allowing for greater enforcement of the MPA. Larger CFAs can generate more resources to finance enforcement but also reduce the size of the no-take reserve. Smaller CFAs leave larger no-take areas, but provide little enforcement. We derive the CFA size that maximizes the conservation outcome, allowing for the possibility that the optimal CFA size is 0 (i.e. no CFA).

The International Union for the Conservation of Nature (IUCN) has created protected area

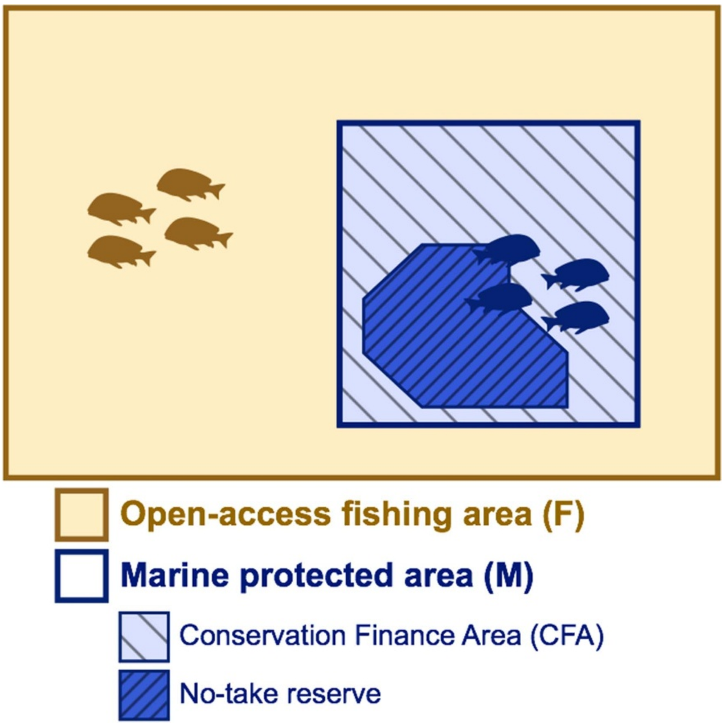

Figure 1. Schematic of a marine protected area (MPA) system with a proposed Conservation Finance Area (CFA). The system is comprised of a general fishing area (F) (for which we assume open-access fishing dynamics) and the total area available for an MPA (M). A fraction of the MPA is designated as a CFA, or lease area. The remainder of the MPA is a no-take reserve. Access revenues from the lease area are used to finance the enforcement of the entire MPA. The lease area receives the spillover of legal-sized fishery target species from the no-take reserve. The CFA need not fully surround the no-take reserve; it may be contained within it or adjacent to it, with spillover connecting them.

management categories to classify protected areas according to their management objectives (IUCN 2013). Under these guidelines, our no-take zone is a Category Ia MPA (Strict Nature Reserve) and the CFA is a category VI area (sustainable use of natural resources). Together, the CFA and the no-take zone come together to form a multi-use MPA. The main difference between our set up and other multi-use MPAs around the world is that proceeds from sustainable fishing in the CFA are explicitly linked to the enforcement and management of the entire MPA (that is, both the CFA and the no-take zone).

3. Bioeconomic model

Our main system is divided into an open access patch (F) and a multi-use MPA patch (M). We use a two-patch stock-dynamic model, where the fish stock in each patch grows independently, such that the discrete-time population growth for the stock in patch i at time t is:

$$g(X_{i,t}) = X_{i,t} + rX_{i,t}\left(1 - \frac{X_{i,t}}{K}\right) - H_{i,t} \qquad (1)$$

where $X_{i,t}$ is the fish biomass in patch i at time t, r is the intrinsic growth rate of the stock, K is the carrying capacity, and $H_{i,t}$ is the harvest from all fleets in patch i at time t. A fraction of the stock in each patch then redistributes to the other patch, and a fraction remains in its origin patch. Movement between the two patches is given by a dispersal matrix:

$$D = \begin{bmatrix} d_{F,F} & d_{M,F} \\ d_{F,M} & d_{M,M} \end{bmatrix} \qquad (2)$$

where $d_{F,F}$ is the fraction of the stock from patch F that remains in patch F, $d_{M,F}$ is the fraction of the stock from patch M that redistributes to patch F, and so on. Therefore, the biomasses in patches F and M at time $t+1$ are given by:

$$X_{F,t+1} = g(X_{F,t})\,d_{F,F} + g(X_{M,t})\,d_{M,F} \qquad (3.1)$$

$$X_{M,t+1} = g(X_{M,t})\,d_{M,M} + g(X_{F,t})\,d_{F,M}. \qquad (3.2)$$

This model of stock biomass allows biomass to accumulate inside M, but it does not account for age structure nor within-time-step dynamics, and it assumes that the stock is uniformly distributed within each patch.

Both legal and illegal harvests are functions of the available biomass and fishing effort. The total harvest in pixel i at time t is the sum of harvests from all fleets fishing in pixel i at time t. Descriptions of each fleet are below, but in general, harvest from fleet j at time t is:

$$H_{j,t} = qE_{j,t}\left[f(X_t, L, D)\right] \qquad (4)$$

where q is catchability, $E_{j,t}$ is fishing effort (days) from fleet j at time t, and $f(X_t,L,D)$ is the fraction of total biomass available to be fished by fleet j, which is a function of X_t (total biomass across both patches at time t), L (size of the CFA), and D (the dispersal matrix). We track two legal fishing fleets. The first legal fleet comprises all fishing effort in patch F (denoted by $E_{F,t}$). The second legal fleet comprises the portion of fishing effort in the CFA (denoted by $E_{L,t}$) which is subject to the per-unit-effort access fee. We also track one illegal fishing fleet, which comprises both the portion of fishing effort in the CFA not subject to the per-unit-effort access fee and all fishing effort in the no-take zone (together denoted as $E_{I,t}$). We assume the illegal fishing fleet is subject to a per-unit-effort expected fine for fishing illegally, defined as the product of the probability of being apprehended (θ) and the fine (ψ). System of equation (5) describes time-t expected profit for each fleet:

$$\Pi_{F,t} = pqE_{F,t}X_{F,t} - cE^{\beta}_{F,t} \tag{5.1}$$

$$\Pi_{L,t} = pqE_{L,t}X_{M,t}L - cE^{\beta}_{L,t} - \chi E_{L,t} \tag{5.2}$$

$$\Pi_{I,t} = pqE_{I,t}\left(X_{M,t} - H_{L,t}\right) - cE^{\beta}_{I,t} - \theta\psi E_{I,t}. \tag{5.3}$$

Here, p is the price of fish, c is a fishing cost parameter, β is a coefficient that determines the shape of the cost curve (values of $\beta > 1$ imply increasing marginal cost of fishing effort), χ is the per-unit-effort access fee levied for fishing in the CFA, θ is the probability of detecting illegal fishing activity, and ψ is the fine.

Rational fishing behavior will result in equal marginal profits from effort in each patch (the 'ideal free distribution'), where effort continues to increase so long as there are profits to be made (Gillis *et al* 1993). In steady-state, marginal profits in all areas will be zero. The differences in steady-state effort across fleets are driven by differences in their cost structure. In open-access areas (i.e. fleet F only) this will depend only on the cost of applying effort (i.e. cE^{β}), while within the MPA it will also depend on the per-unit-effort access fee (for fleet L) and the per-unit-effort expected fine (for fleet I). Steady-state effort in each fleet is:

$$E_F = \left(\frac{pqX_F}{\beta c}\right)^{1/(\beta-1)} \tag{6.1}$$

$$E_L = \left(\frac{pqX_ML - \chi}{\beta c}\right)^{1/(\beta-1)} \tag{6.2}$$

$$E_I = \left(\frac{pq(X_M - H_L) - \theta\psi}{\beta c}\right)^{1/(\beta-1)}. \tag{6.3}$$

Now suppose that the enforcement budget, B, includes an exogenous budget, b, and lease revenue: $B = b + \chi E_L$. We assume that cost per unit enforcement effort is α. This implies a relationship between fishing in the lease zone and enforcement effort:

$$E_E = \frac{b + \chi E_L}{\alpha}. \tag{7}$$

The probability of detecting illegal fishing activity, θ, is a function of enforcement effort and a coefficient, μ, which dictates how fast the probability of being caught changes with respect to enforcement effort. The intuition behind μ is that it effectively scales with the size of the multi-use area (no-take plus CFA): the smaller the area, the more quickly detection increases with enforcement effort, and the larger μ. We specifically assume:

$$\theta = 1 - e^{-\mu E_E}. \tag{8}$$

We assume the manager's objective is to maximize steady-state system wide biomass, which is determined by the total enforcement budget (B), the size of the CFA (L), and the per-unit-effort access fee (χ) (see SI for details).

4. CFA design principles

We simulate different scenarios with varying fines, enforcement costs, fishing costs, and dispersal configurations. In all cases, we find that with no exogenous budget (b) available, a positively sized CFA ($L > 0$) is always optimal, because otherwise there is no enforcement, and therefore no protection. We analytically prove this in the SI (Proposition 1); in our simulation model, system-wide biomass is maximized by designating 25%–50% of the MPA as a CFA under most parameter values (figure 2(A)) (also table S1; figures S1 and S2). When varying one parameter at a time, we find that a larger fine results in smaller optimal CFAs, higher enforcement costs demand larger CFAs, higher costs of fishing require smaller CFAs (but reduce overall biomass), and greater biomass retention requires smaller CFAs (figures 2(B)–(E)).

Certainly, many real-world MPAs have a non-zero enforcement budget, so we next explore whether a CFA is a relevant design feature in the presence of a large, perpetual, and exogenous enforcement budget (b). We find that a sufficiently large exogenous enforcement budget would eliminate the biomass benefit of a CFA, but only if b is large enough to completely deter illegal fishing in the MPA (figure 3). The CFA continues to increase the conservation benefits of the MPA in most simulations exploring interactions between lease-area size and external enforcement budget because leasing displaces more poaching effort—via increasing enforcement and increasing competition for fish—than it introduces via the leases, even when poaching is minimal (well enforced).

Our model considers two other main management levers besides the CFA size: the per-unit-effort access fee (i.e. the lease price) (χ), and the magnitude of the fine (ψ). The market determines the quantity of leases purchased, given the price, the

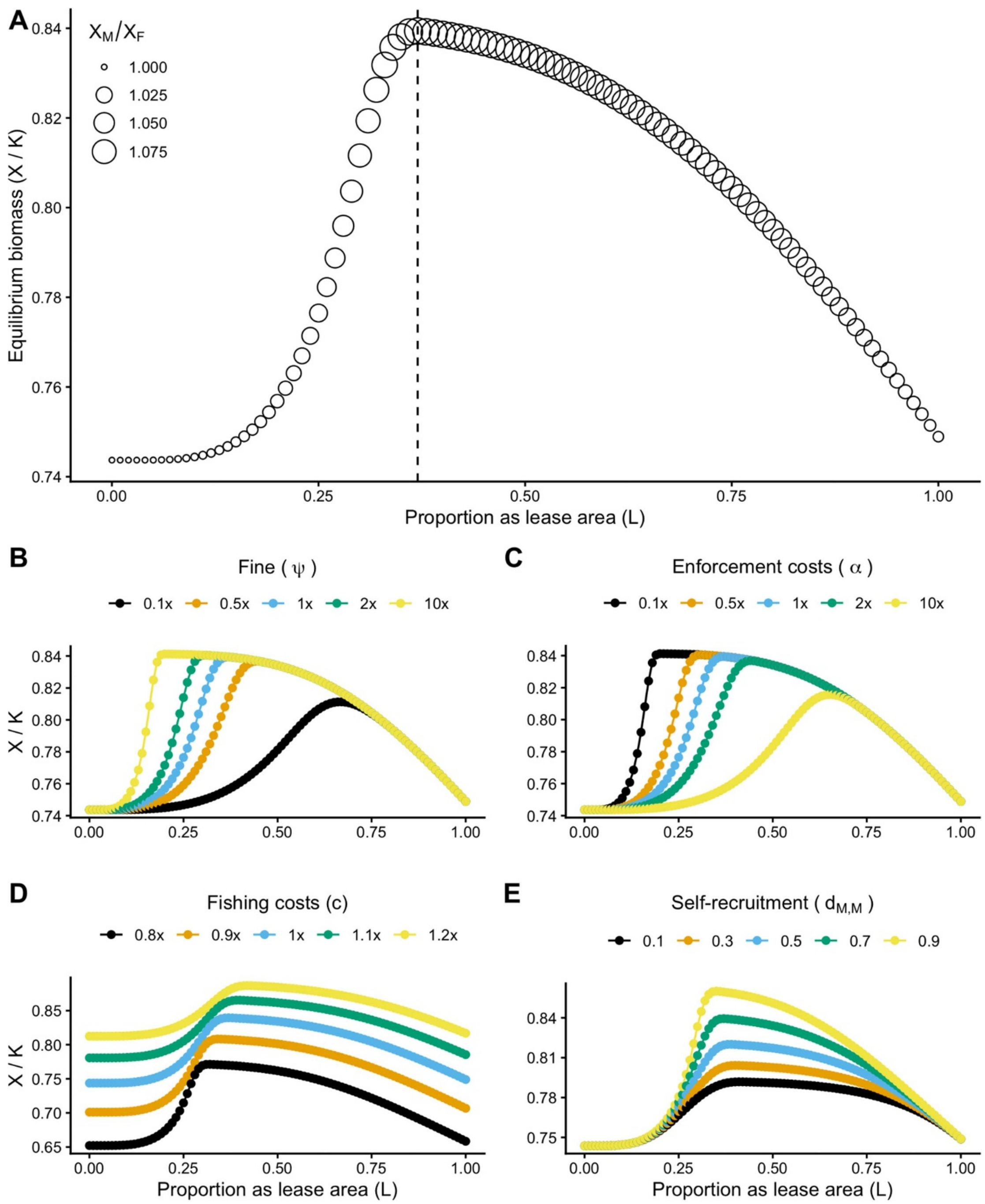

Figure 2. Total equilibrium biomass scaled by carrying capacity (X/K) for different proportions of the MPA (M) designated as a CFA (L). The size of the circles indicates the proportion of total equilibrium biomass in the MPA, relative to that outside (X_M/X_F). Panel (A) shows total equilibrium biomass by CFA size for the reference case parameters (table S1). The dashed line indicates the CFA size corresponding to the highest possible equilibrium biomass. Subsequent panels show the effects of varying different parameters: (B) fine (ψ); (C) variable cost of enforcement (α); (D) variable cost of fishing (c); (E) self-recruitment to the managed area ($d_{M,M}$, i.e. fish offspring from the MPA that remain in the MPA).

biomass premium provided by the MPA, and the size of the lease area. Thus, managers implicitly control the quantity (e.g. they could reduce the number of leases by raising the price). We assume that an MPA manager would jointly set these parameters to maximize her conservation objective. The optimal values vary according to the parameter values of the model (see, e.g. figure 2), but all are positive and finite when b is insufficient (proven analytically in the SI; Proposition 2).

5. Discussion

Financing effective enforcement is a primary challenge to MPA success: a lack of enforcement can significantly erode fish biomass benefits via poaching (Pollnac *et al* 2010). Nations have traditionally relied on philanthropic donations, government budgetary allocations via taxes, or tourism to finance the monitoring and enforcement of MPAs (Berger *et al* 2019) but such resources are insufficient to adequately

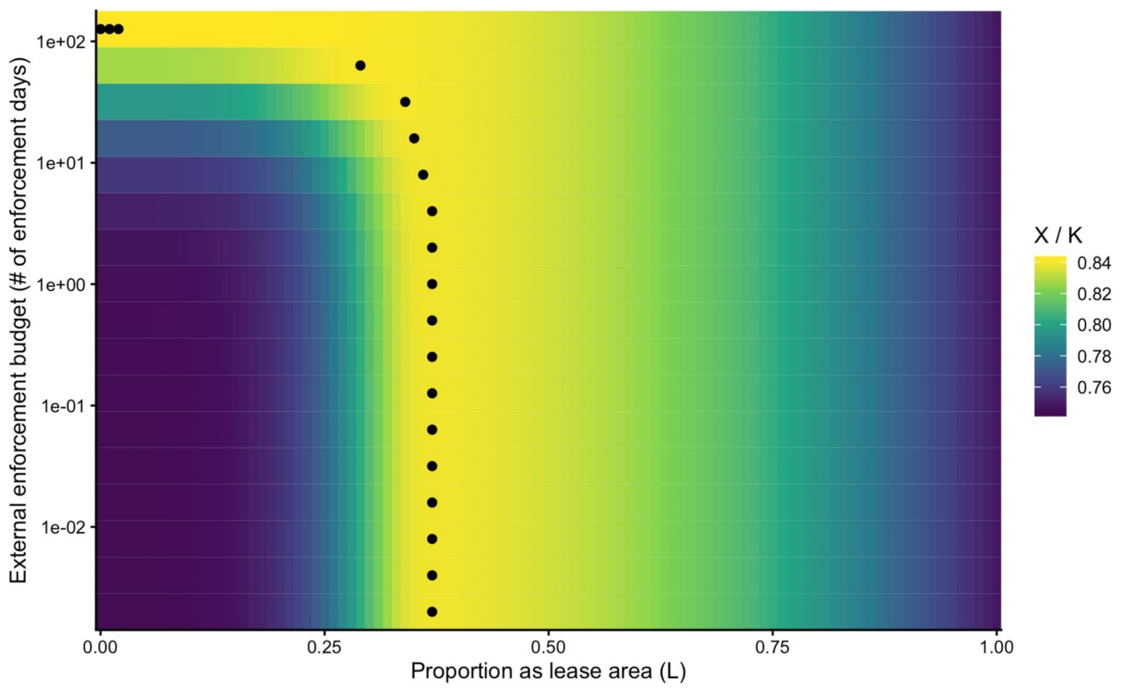

Figure 3. Interaction between lease-area size and external enforcement budget on conservation outcomes. The background color indicates total equilibrium biomass scaled by carrying capacity (X/K) for a range of lease-area sizes (L) and external enforcement budgets (b). The points indicate the lease area sizes corresponding to the maximum attainable equilibrium biomass for each external enforcement budget.

support existing MPAs (Gill *et al* 2017), let alone the massive expansion in MPAs that international targets demand. We propose a new design feature—a CFA—to finance MPA enforcement through fishing lease revenue, and we show that CFAs can increase conservation benefits in any MPA lacking perfect enforcement.

Our contribution to conservation is based on an analysis that is intentionally simplified and strategic, rather than tactical. Tactical implementation of CFAs in real systems must consider a large suite of context-dependent challenges, including the factors driving illegal fishing, the role of fisheries management, and the political and cultural feasibility of the CFA approach, including overcoming barriers to creating multi-agency market systems. None of these challenges are insurmountable, but each will be idiosyncratic in different contexts.

The validity of our proposed CFA approach depends on two core assumptions—that enforcement (i.e. deterring illegal fishing) is (a) possible and (b) enhanced with increased funding recouped from access fees. These two assumptions likely apply in most settings. However, the specific enforcement mechanism in our numerical model—fines—may not always be optimal (Sutinen and Andersen 1985). Fines may not affect illegal fishing decisions if they are set too low (Sykes 1984), violators might not be able to pay fines that are too high (Polinsky and Shavell 1990), and corruption might allow violators to avoid paying (Polinsky and Shavell 2001). The presence of corruption within a fishery management agency may negate either of our core assumptions; corruption has been shown to undermine monitoring and enforcement efforts, pervert licensing schemes (i.e. leases in a CFA system), and disrupt financial flows critical to fisheries management operations (Hanich and Tsamenyi 2009). In some contexts, other factors besides fines may be more predictive of compliance, such as one's perception of the probability of being caught (Furlong 1991). Social, moral, or other normative factors may also play a substantial role in determining compliance (Englander 2019, Oyanedel *et al* 2020), since fishers often comply with regulations even when illegal fishing is lucrative and both penalties and probabilities of detection are low (Kuperan and Sutinen 1998). Socioeconomic conditions affecting how enforcement reduces (or fails to reduce) illegal fishing merits further study.

A second consideration is how fishery management affects the conservation-maximizing size of the CFA. In figures 2 and 3, we assume that the access fee has been set exogenously and is fixed, regardless of the size of the lease area. This is not unrealistic as real-world examples show that access fees are often imperfectly set (Havice 2013). However, it is possible to envision a scenario in which the manager has enough information to be able to set the access fee precisely to achieve a desired biological or economic objective. We find that when the access fee is optimized relative to the size of the lease area, it allows for even more cost-effective conservation with

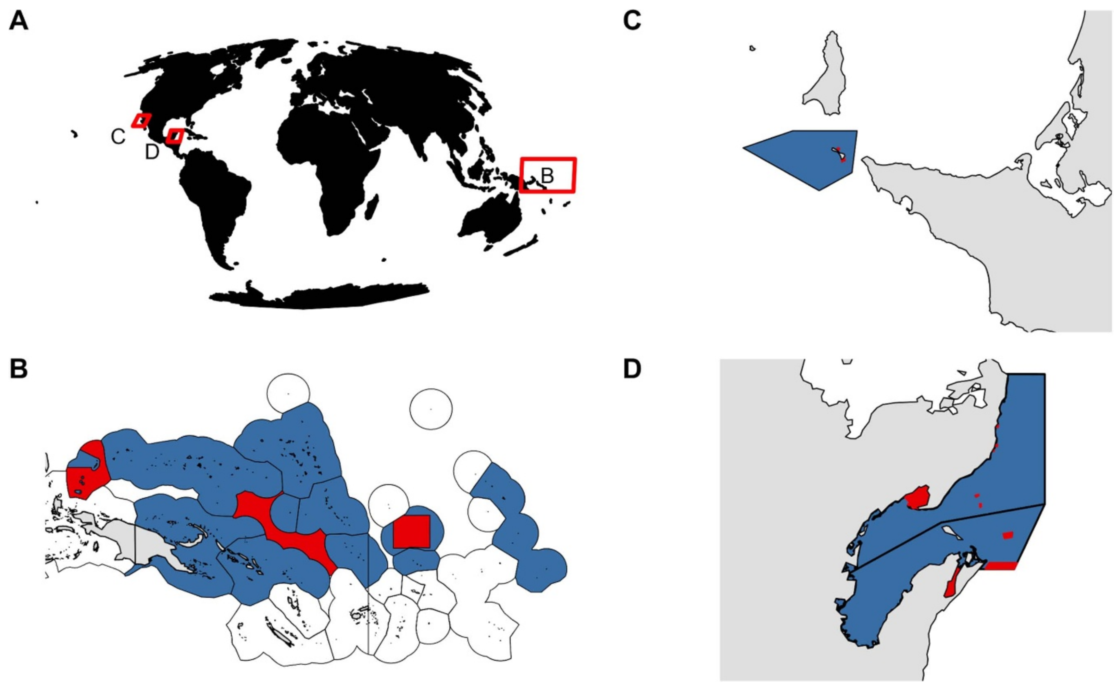

Figure 4. MPAs effectively functioning as CFA systems in large- and small-scale fisheries. Panel (A) shows a global reference map. The PNA region is shown in panel (B). In panel (B), blue polygons show areas where leased fishing is allowed via the Vessel Day Scheme (VDS), and red polygons highlight the location of the Phoenix Islands Protected Area (PIPA, in Kiribati), the Palau National Marine Sanctuary (PNMS, in Palau), and the High Seas Pocket (HSP) formed between the Exclusive Economic Zones of PNA nations. Territorial Use Rights for Fisheries (TURFs) paired with community-based marine reserves (i.e. TURF-reserves) in Mexico are shown for the Baja California Peninsula in panel (C) and the Yucatan Peninsula in panel (D). In panels (C) and (D), the blue polygons show exclusive-access areas held by fishing cooperatives and red polygons show the marine reserves within the TURFs. The fishing cooperatives charge sportfishers to fish in the blue areas.

a CFA (figure S3). Once the size of the CFA is sufficient to deter illegal fishing, very few conservation gains will be made by further increasing its size. This result may be particularly pertinent for implementing a CFA, because relatively smaller lease-areas may be more politically palatable to conservationists (or conversely, relatively larger lease-areas may be more favorable to fishers) (Smith *et al* 2010). Nonetheless, the potential conservation benefits from a CFA are likely insensitive to CFA size if the fishing effort within is well-managed. If surrounding fisheries were not open access (as our model assumes), maximal conservation benefits could be achieved with even smaller CFAs.

CFAs might also have unintended consequences similar to other market-based solutions, like reducing stakeholders' willingness to engage in collective action (Cinner *et al* 2020), potentially eroding social capital, and hindering the effectiveness of other conservation actions. As with any management intervention, it is important to consider not only the biological feasibility of a CFA, but also the socio-cultural context in which it would be implemented. Despite this, there are examples of CFA-like systems that suggest real world feasibility. One such example comes from the Parties to the Nauru Agreement (PNA) who jointly manage tuna fisheries within their waters by leasing fishing rights to purse seiners (Havice 2010). Fishing is off-limits in the Phoenix Islands Protected Area (PIPA, in Kiribati), the Palau National Marine Sanctuary (in Palau), and the High Seas Pocket formed between the Exclusive Economic Zones of PNA nations (figure 4(B)), providing conservation benefits to tuna populations via protection of key habitats (e.g. tuna spawning grounds within PIPA (Hernández *et al* 2019)), and simultaneously providing economic benefits in the way of extracted rents from tuna spillover (Villaseñor-Derbez *et al* 2020). Fishery access fees paid by the purse seiners provide a substantial source of revenue—more than 50% of government revenues in certain PNA countries (e.g. Kiribati and Tuvalu) (Gillett 2016).

Another example comes from small-scale fisheries managed under Territorial Use Rights for Fisheries (TURFs) paired with community-based marine reserves (i.e. TURF-reserves) in Mexico (Villaseñor-Derbez *et al* 2019). Owners of these TURF-reserve systems offer occasional sport fishing tours, in which sport fishers pay an access fee to fish in the TURF but not in its associated reserve (figures 4(C) and (D)). This provides an additional stream of revenue allowing fishers to strengthen the management of their community-based marine reserves (Villaseñor-Derbez *et al* 2018). We recognize that neither of these systems are perfect analogues for our proposed institution (nor infallible management systems—enforcement and compliance challenges remain, particularly in the PNA). Indeed, CFAs differ from both of these systems in that they would explicitly institutionalize the leasing of MPA spillover to finance enforcement, but the underlying use of a user-fee model for public-goods provisioning is similar. We include these two examples because the close conceptual parallels between these real-world systems and CFAs suggest that our proposed institution is a viable policy solution and that effective marine zoning can create financing opportunities to achieve simultaneous fisheries and conservation benefits.

The complexity of problems affecting the ocean requires a diverse set of solutions. While MPAs may benefit biodiversity by spatially managing threats in certain contexts, other strategies, particularly adequate fisheries management and community-based management, can be similarly effective alternatives or complements (Oyanedel *et al* 2016, Oyanedel *et al* 2018, Hilborn 2018, Hilborn *et al* 2020). However, where MPAs are the chosen tool, long-term financing mechanisms to support their operations and management are paramount. Our work shows how a CFA can finance marine conservation, yielding better conservation outcomes than would have been achieved with a reserve alone. This clear funding strategy could accelerate the pace of marine conservation and support its long-term success and sustainability.

Data availability statement

All data and code that support the findings of this study are openly available at the following URL: https://doi.org/10.5281/zenodo.5554977.

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