MPAs and Aspatial Policies in Artisanal Fisheries

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ABSTRACT

Using a spatially explicit framework with low/middle-income country coastal characteristics, we explore whether aspatial policies augment the impact of marine protected areas (MPAs) and identify when MPAs create income burdens on communities. When MPAs are small and budget-constrained, they cannot resolve all of the marinescape's open-access issues, but they can create win-win opportunities for ecological and economic goals at lower levels of enforcement. Aspatial policies—taxes, gear restrictions, license restrictions, and livelihood programs—improve the MPA's ability to generate ecological gains, and licenses and livelihood policies can mitigate MPA-induced income burdens. Managers can use MPA location and enforcement level, in conjunction with the MPA's impact on fish dispersal, to induce exit from fishing and to direct the spatial leakage of effort. Our framework provides further insights for conservation-development policy in coastal settings, and we explore stylized examples in Costa Rica and Tanzania.

Key words: Artisanal fishery, fishery management, leakage, marine protected areas, marine reserves, no-take zones, people–park conflict, spatial bioeconomic model, spatial prioritization.
JEL codes: O13, Q22, Q56, Q57.

INTRODUCTION

Coastal communities in low- and middle-income countries (LMICs) often have poor populations, inefficient labor allocations, and near-open-access fisheries with severe stock depletion (FAO 2020; Berkes et al. 2006). To mitigate open-access overextraction and address resource and development goals, governments employ a variety of *aspatial* policies, such as taxes, gear restrictions, alternative income-generating programs, and licenses (Anderson 1985; Wilen 2000; Kasperski and Holland 2013; Defeo et al. 2016). Governments also employ *spatial* policies, such

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as marine protected areas (MPAs), to address ecological conservation goals and/or economic goals (Pereira et al. 2013; Gaines et al. 2010; Jentoft, Chuenpagdee, and Pascual-Fernández 2011; Sanchirico and Wilen 2001; Pezzey, Roberts, and Urdal 2000). This paper identifies settings in which aspatial policies can improve the effectiveness of MPAs, when MPA size and enforcement are limited. Given the LMIC setting, we also identify the conditions in which MPAs place burdens on local communities.

Previous work has found that governments make MPA decisions while taking the aspatial policy settings—ranging from open-access to well-managed—as given, while fishers make spatially explicit fishing labor decisions in response to both MPA and aspatial policies (Madrigal-Ballestero et al. 2017; Robinson, Albers, and Kirama 2014; Albers et al. 2015). Despite the prevalence of this situation, analysis of the economic and ecological impacts of spatial MPA policies in settings with traditional aspatial marinescape policies based on the spatial reaction of fishers remains limited in the marine economics and policy literature. Our analysis explores this aspect of MPA implementation in LMICs, allowing aspatial policies to interact with both the spatial dispersal of fish and fishers' spatial location choices. For example, as with terrestrial protected areas (PAs), concerns about economic burdens on local communities from restricted fishing access to MPA sites arise (Pollnac, Pomeroy, and Harkes 2001; Carter and Garaway 2014; Madrigal-Ballestero et al. 2017), as do concerns about whether MPAs can produce ecological or economic benefits with low enforcement budgets (Hannesson 1998; Agardy, Notarbartolo, and Christie 2011; Albers et al. 2020).

Based on fieldwork and stakeholder discussions, we further address LMIC artisanal fishery settings in our characterization of fisher decisions and MPA manager constraints (Albers et al. 2020). First, we characterize individual fishers—or boats of fishers—as making a fishing site choice and labor allocation decision between fishing and onshore activities, given heterogenous fishing site distance costs, onshore opportunities, and resource rents in an open-access setting.[1] These individual fishing site and labor allocation decisions aggregate across the marinescape through a spatial Nash equilibrium. Second, we consider budget constraints on each manager's MPA siting and enforcement decisions. Managers select the optimal site and enforcement level based on the expected response of fishers to the MPA and other policies, as a Stackelberg first mover to which the fishers' Nash equilibrium is the best response. In contrast to analyses that assume costless enforcement leads to complete deterrence (e.g., Sanchirico and Wilen 2001), our managers select enforcement levels that, in keeping with the optimal costly enforcement literature (Polinsky and Shavell 2000; Robinson, Kumar, and Albers 2010), may not deter all harvest within the MPA. We model fishers' decisions in response to policy rather than solving for an open-access or optimally managed setting equilibrium condition on fishing effort to examine MPA and aspatial policies that move the coastal system from open access toward a better managed setting.

We use our model to identify how aspatial policies can increase MPA impact and to identify when MPAs create burdens for local communities. We define two managers who make MPA decisions both with and without the presence of aspatial policies. A manager with an ecological goal uses the MPA to increase the stock of fish in the marinescape compared with the stock in the same

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[1] A key feature of our model is that we explicitly model fishers' site choices based on distance costs. While the literature typically models distance using a fixed cost based on the site's location, we explicitly model travel costs by including that fixed cost for *each boat* or fisher traveling to its fishing site.

policy setting without the MPA (henceforth ASL, for avoided stock loss).[2] A manager with an economic goal uses the MPA to increase community income inclusive of both fishing income and onshore wage income, reflecting how LMICs often seek economic development that integrates across sectors in conjunction with MPAs (Jennings 2009; Albers et al. 2020). Further, we characterize the economic impact of ASL-maximizing MPAs and the ecological impact of the income-maximizing MPAs across aspatial policy settings.

We define policy insights for LMIC coastal management based on how MPA characteristics and aspatial policy settings create exit from fishing and interact with fish dispersal to induce both marginal increases in fishing and spatial leakage of fishing effort in non-MPA locations. We show that aspatial policies can complement MPAs by inducing changes in the amount and distribution of fishing effort due to the presence of a spatial process (fish dispersal) and spatial decisions (fishing site choice) and make it easier to achieve MPA goals in the presence of budget constraints. We identify settings in which MPAs lead to win-win situations versus trade-offs between ecological and economic outcomes, with particular emphasis on whether MPAs generate economic burdens for local communities. In trying to achieve win-win policies, some aspatial policies, such as taxes, introduce a cost burden on local communities while other aspatial policies, such as alternative income-generating projects, lead to higher incomes and higher fish stocks. We adapt our framework to explore two stylized case examples for Tanzania and Costa Rica, which provide further insight into coastal management for conservation and economic development in LMIC settings.

MODEL

We use a modified version of the spatial bioeconomic model of fishers' decisions developed by Albers et al. (2020). Specifically, they use their model to explore optimal siting, enforcement, and sizing for MPAs in a setting with no aspatial policies. Here, we remove the sizing choice (i.e., we focus on one-site MPAs) and explore optimal siting and enforcement for MPAs in a setting with aspatial policies. The model comprises a marinescape of fishing sites with one village; fish dynamics with rook-contiguous density dispersal; N villagers making labor allocation and fishing site choices that then integrate in a spatial Nash equilibrium; fixed aspatial policies that alter fisher decisions; and two managers who site MPAs with different goals subject to budget constraints.

MARINESCAPE AND FISH

We define the biological and spatial setting as an adult fish metapopulation structure with density dispersal across an $R \times C$ matrix (i.e., marinescape) in which the centroid of each cell corresponds to a fishing site i, indexed from 1 to $(R \cdot C)$. Within this marinescape, fish stocks in each site i change over time according to

$$\boldsymbol{X}_{t+1} = \boldsymbol{X}_t + \mathcal{g}(\boldsymbol{X}_t, \boldsymbol{K}) + \boldsymbol{D}\boldsymbol{X}_t - \boldsymbol{H}_t, \tag{1}$$

where $\boldsymbol{X_t}$ is an $(R \cdot C) \times 1$ vector of fish stocks x_i at time t, the logistic function $\mathcal{g}(\boldsymbol{X_t}, \boldsymbol{K})$ depicts natural population net growth at each site given current stocks $\boldsymbol{X_t}$ and carrying capacity $\boldsymbol{K}$, $\boldsymbol{H}_t$ is

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[2] We focus on the level of stock with the MPA relative to the level of stock relative to the no-MPA setting because policy effectiveness is measured by the impact or additionality of the policy, rather than by a particular level (Pfaff et al. 2014). The choice could be adapted for alternative ecological goals, such as reef protection, that aim to protect a particular site instead of a mobile resource.

an $(R \cdot C) \times 1$ vector of the sum of all individual fishers' harvests from each site at time t, and $\boldsymbol{D}$ is a dispersal matrix reflecting first-order rook density dispersal.[3] In our case of closed borders, $\boldsymbol{D}$ is an $(R \cdot C) \times (R \cdot C)$ dispersal matrix. We find the biological steady state ($\boldsymbol{X_{ss}}$, defined by $\boldsymbol{X}_t = \boldsymbol{X}_{t+1}$) formed by this biology and fishers' actions (online appendix A, open border case).

VILLAGERS

We include one village with N identical villagers. Each villager, n, maximizes their income by choosing in which one site (i) to fish if they choose to fish and their labor allocation between onshore wage labor and fishing, while facing labor, technological, and game-theoretic constraints. First, total available labor, L_n, constrains the time spent working for wage, $l_{w,n}$, fishing, $l_{f,i,n}$, and traveling to the fishing site, $l_{d(i),n}$:

$$L_n \geq l_{w,n} + l_{f,i,n} + l_{d(i),n},$$

where fishers face heterogeneous travel costs $l_{d(i)}$. Second, fishers face a standard harvest function relating to the fishing labor time in the site ($l_{f,i,n}$), the stock of fish in site (x_i), and the catchability coefficient (q) as a function of gear restrictions (g) that reduce catchability:

$$h_{i,n} = l_{f,i,n} x_i q(g).$$

The total harvest in each site is the sum of all fishers' harvests in the site i:

$$H_i = \sum_n h_{i,n},$$

which enters the fish stock equation above (equation 1). We constrain each villager to fish in at most one site.[4] All n villagers maximize their expected individual income based on the expected value of harvesting within an MPA and facing a probability of enforcement and fines:

$$\max_{i,l_{f,i},l_w} EV = p(1-\tau_h)h(g)_i(1-\phi_i) - G(p_G, \tau_G, l_d) + w(l_w)^\gamma - \phi_i F. \tag{2}$$

Fishing is incentivized by higher fish prices (p), lower landing taxes (τ_h), lower enforcement levels if the fishing site is protected (ϕ_i), lower gas costs($G(\cdot)$) via lower gas prices (p_G) or lower gas taxes (τ_G), higher catchability coefficient via less gear restrictions (g), lower onshore wages (w), and lower fines when caught fishing in a protected site (F). We model onshore market labor imperfections with $\gamma < 1$.[5]

Third, all villagers choose their fishing site (or wage specialization in the village) subject to a game-theoretic constraint on their fishing site choice. Fisher n best responds to the setting and

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[3] We use rook dispersal—spatial movement of fish between sites with shared borders but not through corners as in queen dispersal—because it is a common method and because it elucidates the role of dispersal. The centroids of each grid cell are farther apart for diagonal neighbors than for border neighbors, which implies that dispersal might be less pronounced between diagonal neighbors, but our use of rook dispersal likely overstates the level of difference between that dispersal by setting it to zero for the diagonal.

[4] This choice is intended to make the role of spatial effort leakage more visible.

[5] This parameter implies that the first units of labor spent in non-fishing activities have a high value. We use this parameter because most fishers in our interviews stated that they undertake non-fishing activities like subsistence agriculture because of market failures and subsistence requirements (Robinson, Albers, and Kirama 2014). With this parameter, no individual specializes in fishing completely. Similar suggestions of the importance of having some labor time for nonmarket activities lead to the use of a similar structure in terrestrial settings (Sterner, Robinson, and Albers 2018; Albers et al. 2019).

other fishers' decisions by choosing both a fishing site i and a fishing labor allocation, as summarized by $l_{f,i,n}$. A spatial Nash equilibrium results when fisher n's expected value from fishing in site $i^{\star}$ given all other fishers' siting and labor decisions is greater than the expected value of fishing in any other site, $-i$, given all other fishers' decisions, for all n fishers:

$$EV\left(l_{f,i\star,n} | l_{f,i,-n}\right) \geq EV\left(l_{f,-i,n} | \ l_{f,i,-n}\right), \forall \ n,$$

where $-n$ indexes all other villagers and $-i$ indexes all other fishing sites. Individual fisher decisions indirectly depend on other fishers' site decisions and harvest through the steady-state equilibrium stock effect. Given this interaction of villagers' decisions in determining the steady state, a steady-state spatial Nash equilibrium defines the fishing locations and fishing labor for each villager, in response to the policy setting.

ASPATIAL POLICIES

We consider a range of policy levels for each aspatial policy individually, as characterized by varying the policy parameters (τ_h, τ_G, F, g, w, m), where the first five parameters represent aspatial policies as defined above. Parameter m is the number of licenses available for fishing in the marinescape, which limits the number of fishers, N_f, who are permitted to fish in the marinescape. We report results for a high level and a low level of each policy, such as a high and a low landings tax, which defines two aspatial policy settings in which we explore the optimal siting and enforcement for an MPA (online appendices E–I, aspatial policy parameter analysis across a range of values).

MPA MANAGERS

As above, we consider two types of managers with different goals; the ASL-maximizing manager maximizes avoided aggregate fish stock losses across the marinescape and the income-maximizing manager maximizes total income from both fishing and non-fishing activities. All managers' maximization decisions are subject to fish dispersal (equation 1) and the best response of the fishers' optimization and Nash equilibrium, which determine total harvest, $\boldsymbol{H}$, and stock level, $\boldsymbol{X}$ (equation 2).

When considering an MPA, the manager chooses one site, $s_i = 1$, of the vector, $\boldsymbol{S}$, of marinescape sites and chooses the MPA's enforcement level, $\phi \in [0, 1]$, where $\phi = 1$ implies a probability of getting caught and punished of 1 and $\phi = 0$ implies that the site is not an MPA (or it is a paper park with no enforcement). To capture budget constraints and trade-offs, the manager chooses the level ϕ, where intermediate levels of enforcement, $0 < \phi < 1$, can deter some or all illegal harvesting. The manager incurs a total enforcement cost, β, from marginal cost c per unit ϕ, in addition to a distance cost capturing the gas cost spent traveling to the protected site (Nøstbakken 2008; Milliman 1986; Sutinen and Andersen 1985) subject to an often-binding budget constraint $B \geq \beta$:

$$\beta = \sum_i s_i \left[c\phi + G\left(l_{d(i)}, \ p_g\right)\right].$$

Each manager accounts for the fishers' responses to the MPA; thus, the manager optimizes over the outcome of fishers' Nash equilibrium fishing site and labor choices in response to an MPA at the steady state for fish stocks. Specifically, the ASL-maximizing manager chooses the site to protect and the enforcement level at which to protect the site to maximize avoided stock loss in the marinescape:

$$\max_{\{S,\phi\}} \sum_i [x_i - x_{i,AP}],$$

where the avoided stock loss is computed relative to the stock, x_{AP}, in the relevant aspatial policy with no-MPA setting. We find ASL-maximizing MPAs in a setting without aspatial policies by comparing with open access without aspatial policies (i.e., a setting in which $\tau_h = \tau_G = \phi_i = F = g = 0$, and no restrictions on the number of fishers allowed to fish, m).

The income-maximizing manager chooses the site to protect and the MPA site's enforcement level to maximize community income,

$$\max_{\{S,\ \phi\}} \left\{ \sum_{i=1}^{R\cdot C} [p(1-\tau_h)H_i(1-\phi_i) - G(p_G, \tau_G, l_d) - \phi_i F\ ] + \sum_{n=1}^{N} w(l_{w,n}^{\gamma}) \right\},$$

subject to the same budget constraints and ecological and fisher descriptions as the ASL-maximizing manager. Both managers are constrained by the number of potential fishers ($N_f \leq m$) and gear restrictions g.

SOLUTION METHOD AND PARAMETERS

We use numerical methods in MATLAB to solve the villagers' optimization and Stata to solve the manager's optimization for the spatial setting of a 2 × 3 grid (i.e., six fishing sites), with $N = 15$, and travel time as the Cartesian distance from the village to the centroid of the fishing site (parameters in table 1). We solve for the spatial Nash equilibrium of the best response to the policy setting at the long-run biological (i.e., fish stock) steady state (see Albers et al. [2020] for solution method details). This number of fishers and fishing sites creates a large enough marinescape to

Table 1. Parameter Values

Description	Parameter	Value (Policy Range)
No. of columns (moving along the coast)	–	3
No. of rows (moving out to sea)	–	2
Width of each column	–	3
Width of each row	–	2.5
Position of village by column	–	1
Number of villagers	N	15 (1–9)
Intrinsic growth rate	g	0.4
Dispersal coefficient (from Smith, Sanchirico, and Wilen [2009])	m	0.4
Price of fish	p	1
Wage rate for non-fishing labor	w	1.2 (1.4–2.2)
Wage parameter (opportunity cost of time)	γ	0.6
Total time available per person	L	24
Catchability coefficient	$q_i, \forall i$	0.009 (0.008–0.003)
Carrying capacity for each site	$K_i, \forall i$	100
Cost of $\phi_i = 1$ for site 1	c	29.25
Gas price	p_g	0.2 (0.4–1)
Fine	F	0
Fine (Costa Rica)	F	1 (2–4)
Landing tax	τ_h	0 (0.1–0.4)
Enforcement budgets	B	0, 1, 3, 10, 60

explore settings in which fishers have the opportunity to choose sites near/far from the single village or from the MPA to explore how fishing effort "leaks" across the landscape in response to MPAs and dispersal.

RESULTS AND DISCUSSION

Here, we solve this model for different parameter values to develop insights about MPA decisions, both without and with aspatial policies, and targeting either avoided stock losses (ASL) or income gains. We determine the no-policy open-access spatial equilibrium for the baseline, explore the (budget constrained) optimal one-site MPAs and enforcement level, describe the impact on ASL and income of five aspatial policies, and consider the MPA choices within a setting with aspatial policies. Then, we present results across different types of aspatial policies, synthesize those results to characterize the aspects of importance to policy, discuss when MPAs are an income burden to local communities, and discuss whether these aspatial policies help MPAs achieve their goals. In another section, we explore stylized case examples that reflect environment-development coastal policy issues in Costa Rica and Tanzania.

BASELINE ANALYSIS: OPEN ACCESS

In the baseline open-access case, four fishers respond to travel costs by choosing to fish in the site closest to the village, site 1 (the no-MPA column in figures 1 and 2 contains the total fishing labor in each site and the number of fishers in each site; online appendix, figure D1). Although the total amount of fishing labor in that site is the marinescape's highest level of fishing effort, each fisher in site 1 allocates less time to fishing and more time to wage labor than fishers in other sites, despite the travel costs to those sites. These travel costs—opportunity cost of time and gas costs—ensure that no fishers choose to fish in site 6 (Albers et al. 2020). Sites 2 and 5 support two fishers and high levels of total fishing effort because of the dispersal of fish from neighboring sites within the marinescape, while sites 3 and 4 each contains a single fisher and lower levels of total fishing effort than other fished sites. Of the 15 villagers, five do not dedicate any time to fishing labor and instead specialize in wage labor.

MPAS WITHOUT ASPATIAL POLICIES

For our two MPA managers, ASL-maximizing and income-maximizing, we solve the model to determine the optimal MPA site and enforcement level across a range of budgets including unconstrained (figures 1 and 2, respectively). We define a "low" budget as 1, a "moderate" budget as 3, a "high" budget as 10, and unlimited budget as a budget that does not constrain managers. The managers use their two policy tools—the location of the MPA and the level of enforcement—in conjunction with fish dispersal and fisher distance costs to change fisher behavior to increase ASL or income. At the marinescape level, these MPA tools create several reactions: exit from fishing; marginal decreases in fishing within the MPA at the intensive margin; post-MPA fish dispersal that supports increased fishing effort in dispersed-to sites at the intensive margin; and exit from the MPA and spatial reallocation of fishing effort, or spatial leakage of effort at the extensive margin. Because of the fixed distance costs associated with accessing a site, a particular level of enforcement in a location generates a discrete reduction in fishing effort when it induces exit from fishing itself or when it induces exit from the MPA and spatial leakage of that effort. That spatial leakage of effort responds to dispersal but can impose higher distance costs if the leakage occurs to more distant sites, which reduces the time remaining for fishing and increases distance costs.

	Budget				
	No MPA	Low	Moderate	High	Unlimited
1. Baseline	5	6 (+1)	6 (+1)	6 (+1)	6 (+1)
	48.0 31.3 16.0 (4) (2) (1) 16.1 32.0 0.0 (1) (2) (0)	42.2 32.0 16.0 (-1) (=) (=) 16.4 32.1 0.0 (=) (=) (=)	41.4 47.7 0.0 (-1) (+1) (-1) 16.9 16.5 15.4 (=) (-1) (+1)	28.5 46.2 15.9 (-2) (+1) (=) 17.3 31.9 0.0 (=) (=) (=)	0.0 75.1 0.0 (-4) (+3) (-1) 33.4 15.7 15.2 (+1) (-1) (+1)
Enforcement	0	0.03	0.06	0.28	0.41
2. Low Landing Tax	7	8 (+1)	8 (+1)	9 (+2)	9 (+2)
	52.1 16.1 15.3 (4) (1) (1) 0.0 31.5 0.0 (0) (2) (0)	39.2 32.4 0.0 (-1) (+1) (-1) 15.9 16.3 0.0 (+1) (-1) (=)	39.2 32.4 0.0 (-1) (+1) (-1) 15.9 16.3 0.0 (+1) (-1) (=)	14.3 47.9 0.0 (-3) (+2) (-1) 17.2 16.2 0.0 (+1) (-1) (=)	14.3 47.9 0.0 (-3) (+2) (-1) 17.2 16.2 0.0 (+1) (-1) (=)
Enforcement	0	0.03	0.03	0.32	0.32
3. High Landing Tax	10	11 (+1)	11 (+1)	12 (+2)	12 (+2)
	38.4 15.6 0.0 (3) (1) (0) 0.0 15.3 0.0 (0) (1) (0)	39.7 16.3 0.0 (=) (=) (=) 0.0 0.0 0.0 (=) (-1) (=)	39.7 16.3 0.0 (=) (=) (=) 0.0 0.0 0.0 (=) (-1) (=)	0.0 32.0 0.0 (-3) (+1) (=) 16.3 0.0 0.0 (+1) (-1) (=)	0.0 32.0 0.0 (-3) (+1) (=) 16.3 0.0 0.0 (+1) (-1) (=)
Enforcement	0	0.02	0.02	0.29	0.29
4. Low Gear Restriction	6	6 (=)	7 (+1)	8 (+2)	8 (+2)
	51.3 45.1 0.0 (4) (3) (0) 15.8 15.8 0.0 (1) (1) (0)	60.2 31.6 0.0 (+1) (-1) (=) 15.7 16.0 0.0 (=) (=) (=)	52.4 46.8 0.0 (=) (=) (=) 16.4 0.0 0.0 (=) (-1) (=)	0.0 61.9 0.0 (-4) (+1) (=) 31.9 15.5 0.0 (+1) (=) (=)	0.0 61.9 0.0 (-4) (+1) (=) 31.9 15.5 0.0 (+1) (=) (=)
Enforcement	0	0.03	0.08	0.33	0.33
5. High Gear Restriction	8	8 (=)	8 (=)	9 (+1)	9 (+1)
	52.8 31.0 0.0 (4) (2) (0) 15.4 0.0 0.0 (1) (0) (0)	65.3 15.7 0.0 (+1) (-1) (=) 0.0 15.5 0.0 (-1) (+1) (=)	75.2 0.0 0.0 (+2) (-2) (=) 0.0 15.7 0.0 (-1) (+1) (=)	24.8 46.1 0.0 (-2) (+1) (=) 16.1 0.0 0.0 (=) (=) (=)	24.8 46.1 0.0 (-2) (+1) (=) 16.1 0.0 0.0 (=) (=) (=)
Enforcement	0	0.03	0.1	0.24	0.24
6. Low Gas Tax	8	9 (+1)	9 (+1)	9 (+1)	9 (+1)
	44.9 35.4 0.0 (3) (2) (0) 17.3 17.4 0.0 (1) (1) (0)	50.6 35.7 0.0 (=) (=) (=) 0.0 17.7 0.0 (-1) (=) (=)	50.6 35.7 0.0 (=) (=) (=) 0.0 17.7 0.0 (-1) (=) (=)	50.6 35.7 0.0 (=) (=) (=) 0.0 17.7 0.0 (-1) (=) (=)	0.0 69.0 0.0 (-3) (+2) (=) 35.3 0.0 0.0 (+1) (-1) (=)
Enforcement	0	0.01	0.01	0.01	0.37
7. High Gas Tax	10	10 (=)	10 (=)	11 (+1)	11 (+1)
	53.3 18.9 0.0 (3) (1) (0) 0.0 17.9 0.0 (0) (1) (0)	52.1 36.8 0.0 (=) (+1) (=) 0.0 0.0 0.0 (=) (-1) (=)	52.1 36.8 0.0 (=) (+1) (=) 0.0 0.0 0.0 (=) (-1) (=)	17.9 37.9 0.0 (-2) (+1) (=) 18.8 0.0 0.0 (+1) (-1) (=)	17.0 38.0 0.0 (-2) (+1) (=) 18.8 0.0 0.0 (+1) (-1) (=)
Enforcement	0	0.02	0.02	0.34	0.4
8. Low Wage	8	9 (+1)	9 (+1)	10 (+2)	10 (+2)
	34.4 29.3 0.0 (3) (2) (0) 14.5 15.1 0.0 (1) (1) (0)	39.3 29.6 0.0 (=) (=) (=) 0.0 15.7 0.0 (-1) (=) (=)	35.5 31.0 0.0 (=) (=) (=) 15.5 0.0 0.0 (=) (-1) (=)	0.0 44.6 0.0 (-3) (+1) (=) 16.4 15.1 0.0 (=) (=) (=)	0.0 44.6 0.0 (-3) (+1) (=) 16.4 15.1 0.0 (=) (=) (=)
Enforcement	0	0.02	0.06	0.33	0.33
9. High Wage	10	11 (+1)	11 (+1)	12 (+2)	12 (+2)
	35.2 14.6 0.0 (3) (1) (0) 0.0 14.4 0.0 (0) (1) (0)	36.3 15.4 0.0 (=) (=) (=) 0.0 0.0 0.0 (=) (-1) (=)	36.3 15.4 0.0 (=) (=) (=) 0.0 0.0 0.0 (=) (-1) (=)	0.0 30.1 0.0 (-3) (+1) (=) 15.4 0.0 0.0 (+1) (-1) (=)	0.0 30.1 0.0 (-3) (+1) (=) 15.4 0.0 0.0 (+1) (-1) (=)
Enforcement	0	0.01	0.01	0.26	0.26
10. Low License Restriction	6	6 (=)	6 (=)	6 (=)	6 (=)
	42.5 31.8 16.0 (3) (2) (1) 16.4 32.1 0.0 (1) (2) (0)	58.0 17.0 16.2 (+1) (-1) (=) 0.0 47.6 0.0 (-1) (+1) (=)	58.0 17.0 16.2 (+1) (-1) (=) 0.0 47.6 0.0 (-1) (+1) (=)	53.8 16.3 16.3 (+1) (-1) (=) 16.2 33.0 0.0 (=) (=) (=)	0.0 75.1 0.0 (-3) (+3) (-1) 33.4 15.7 15.2 (+1) (-1) (+1)
Enforcement	0	0.03	0.03	0.15	0.41
11. High License Restriction	11	11 (=)	11 (=)	11 (=)	11 (=)
	39.4 19.1 0.0 (2) (1) (0) 0.0 18.0 0.0 (0) (1) (0)	39.4 19.1 0.0 (=) (=) (=) 0.0 17.9 0.0 (=) (=) (=)	39.5 18.8 0.0 (=) (=) (=) 0.0 18.0 0.0 (=) (=) (=)	39.5 18.8 0.0 (=) (=) (=) 0.0 18.0 0.0 (=) (=) (=)	39.5 18.8 0.0 (=) (=) (=) 0.0 18.0 0.0 (=) (=) (=)
Enforcement	0	0.03	0.09	0.09	0.09
12. Low Fine	5	6 (+1)	6 (+1)	6 (+1)	6 (+1)
	48.0 31.3 16.0 (4) (2) (1) 16.1 32.0 0.0 (1) (2) (0)	42.2 32.0 16.0 (-1) (=) (=) 16.4 32.1 0.0 (=) (=) (=)	41.4 47.7 0.0 (-1) (+1) (-1) 16.9 16.5 15.4 (=) (-1) (+1)	28.5 46.2 15.9 (-2) (+1) (=) 17.3 31.9 0.0 (=) (=) (=)	0.0 75.1 0.0 (-4) (+3) (-1) 33.4 15.7 15.2 (+1) (-1) (+1)
Enforcement	0	0.03	0.06	0.28	0.38
13. High Fine	5	6 (+1)	6 (+1)	6 (+1)	6 (+1)
	48.0 31.3 16.0 (4) (2) (1) 16.1 32.0 0.0 (1) (2) (0)	42.2 32.0 16.0 (-1) (=) (=) 16.4 32.1 0.0 (=) (=) (=)	41.4 47.7 0.0 (-1) (+1) (-1) 16.9 16.5 15.4 (=) (-1) (+1)	0.0 75.1 0.0 (-4) (+3) (-1) 33.4 15.7 15.2 (+1) (-1) (+1)	0.0 75.1 0.0 (-4) (+3) (-1) 33.4 15.7 15.2 (+1) (-1) (+1)
Enforcement	0	0.03	0.05	0.34	0.34

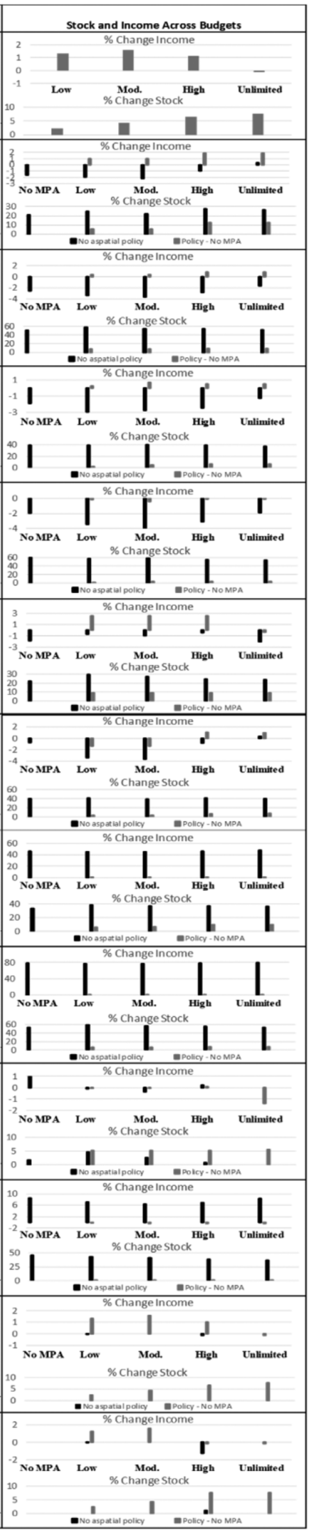
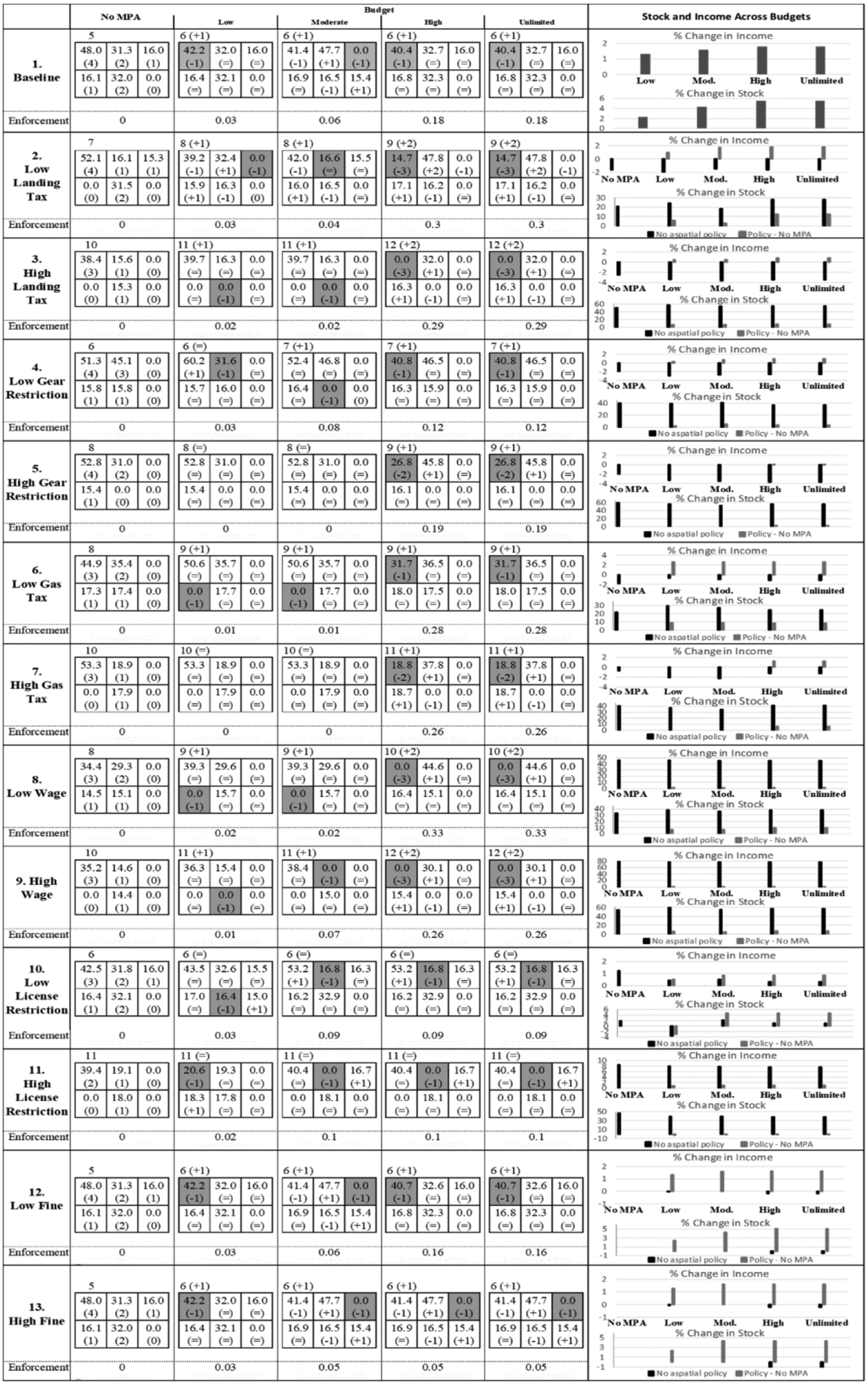


Figure 1

The ASL-maximizing manager and the income-maximizing manager make the same MPA decisions at low and moderate enforcement budgets. At the low budget (1), the optimal one-site MPA is sited nearest the village in site 1 with the entire enforcement budget spent (figures 1 and 2, column 1). The MPA induces one fisher to exit fishing entirely, with a decrease in total fishing effort there and a related increase in fish stock, and the MPA creates dispersal that supports marginal increases in fishing effort in neighboring sites. That increased fishing effort outside of the MPA partially offsets the overall gains in ASL on the marinescape. The enforcement level in the MPA is not high enough to deter fishing in the MPA. At a moderate budget, both managers locate the MPA farther away from the village where the higher enforcement budget and the location's impact on fisher distance costs completely deter fishing in the MPA and create exit from fishing (figures 1 and 2, column 3). Complete deterrence in site 3 leads to dispersal that spreads fishers across the marinescape—spatial reallocation of fishing effort to those sites (2 and 6) from other sites (1 and 5)—which corrects some of the open-access overextraction to increase incomes. Across all fishers, the decrease in distance costs from spatial leakage of effort from site 3 to site 2 is offset by the increase in distance costs from spatial leakage of effort from site 5 to site 6, but the total impact of distance costs and deterrence of fishing in the MPA increases ASL. The dispersal from the no-fishing MPA induces fishing in the previously unfished site at the highest distance from the village. The managers do not choose an MPA in site 1 at the moderate budget level because additional enforcement in that site does not create exit from fishing and instead causes spatial leakage of effort to other sites. Higher distance costs to site 3 than to site 1 mean that lower levels of enforcement deter fishing in the MPA in site 3 but not in site 1 (Albers 2010; Albers et al. 2020; Albers et al. 2015). The ASL- and income-maximizing managers pursue the same MPAs at low and moderate budgets, and the outcomes achieve both income and ecological (ASL) increases—win-win scenarios across economic and ecological gains—and the MPAs are beneficial rather than a burden to local communities.

At high and unlimited enforcement budgets, the decisions of the two manager types diverge in terms of the enforcement level chosen. Although both managers choose site 1 nearest the village as the MPA, the ASL-maximizing manager uses higher enforcement levels than the income-maximizing manager. The ASL-maximizing manager uses their entire budget until the MPA's enforcement deters all fishing in the MPA located in site 1 (figure 1, unlimited column). This highly enforced MPA cannot induce further exit from the fishery beyond the exit of one fisher

Figure 1. ASL-Maximizing Manager's Optimal MPA with Aspatial Policies. ASL-maximizing manager's optimal MPA siting and enforcement across enforcement budgets for different aspatial policy levels. The first column depicts the no-MPA distribution of fishers and effort. The total fishing labor in each site is displayed in each box (as a decimal). The number of villagers who choose not to fish is indicated by that number in the village location above the marinescape, with the change in that number from the no-MPA case in parentheses for each budget. The number of fishers in each site is identified in the marinescape figure for the no-MPA column in parentheses below the fishing effort, and changes in that number of fishers from the no-MPA baseline are indicated by the parenthetical =, +, and – values below the fishing effort for each MPA budget. The highlighted site is the optimal MPA site for the ASL-maximizing manager for each budget level. The last column depicts the percentage change in income and percentage change in stock that the MPA causes at each budget level; the black bar compares with the open access with no-MPA case (baseline row 1, no-MPA column) and the gray bar compares with the no-MPA outcome for that row's policy setting. The low wage is 50% above the baseline and the high wage is 83% above the baseline. See table 2 for aspatial policy levels. (The fine details in many of the figures in this article may be difficult to discern. Please refer to the online version or request digital figures from the lead author.)



	No MPA	Budget			
		Low	Moderate	High	Unlimited
1. Baseline	5 48.0 31.3 16.0 (4) (2) (1) 16.1 32.0 0.0 (1) (2) (0)	6 (+1) 42.2 32.0 16.0 (-1) (=) (=) 16.4 32.1 0.0 (=) (=) (=)	6 (+1) 41.4 47.7 0.0 (-1) (+1) (-1) 16.9 16.5 15.4 (=) (-1) (+1)	6 (+1) 40.4 32.7 16.0 (-1) (=) (=) 16.8 32.3 0.0 (=) (=) (=)	6 (+1) 40.4 32.7 16.0 (-1) (=) (=) 16.8 32.3 0.0 (=) (=) (=)
Enforcement	0	0.03	0.06	0.18	0.18
2. Low Landing Tax	7 52.1 16.1 15.3 (4) (1) (1) 0.0 31.5 0.0 (0) (2) (0)	8 (+1) 39.2 32.4 0.0 (-1) (+1) (-1) 15.9 16.3 0.0 (+1) (-1) (0)	8 (+1) 42.0 16.6 15.5 (-1) (=) (=) 16.0 16.5 0.0 (+1) (-1) (=)	9 (+2) 14.7 47.8 0.0 (-3) (+2) (-1) 17.1 16.2 0.0 (+1) (-1) (=)	9 (+2) 14.7 47.8 0.0 (-3) (+2) (-1) 17.1 16.2 0.0 (+1) (-1) (=)
Enforcement	0	0.03	0.04	0.3	0.3
3. High Landing Tax	10 38.4 15.6 0.0 (3) (1) (0) 0.0 15.3 0.0 (0) (1) (0)	11 (+1) 39.7 16.3 0.0 (=) (=) (=) 0.0 0.0 0.0 (=) (-1) (=)	11 (+1) 39.7 16.3 0.0 (=) (=) (=) 0.0 0.0 0.0 (=) (-1) (=)	12 (+2) 0.0 32.0 0.0 (-3) (+1) (=) 16.3 0.0 0.0 (+1) (-1) (=)	12 (+2) 0.0 32.0 0.0 (-3) (+1) (=) 16.3 0.0 0.0 (+1) (-1) (=)
Enforcement	0	0.02	0.02	0.29	0.29
4. Low Gear Restriction	6 51.3 45.1 0.0 (4) (3) (0) 15.8 15.8 0.0 (1) (1) (0)	6 (=) 60.2 31.6 0.0 (+1) (-1) (=) 15.7 16.0 0.0 (=) (=) (=)	7 (+1) 52.4 46.8 0.0 (=) (=) (=) 16.4 0.0 0.0 (=) (-1) (0)	7 (+1) 40.8 46.5 0.0 (-1) (=) (=) 16.3 15.9 0.0 (=) (=) (=)	7 (+1) 40.8 46.5 0.0 (-1) (=) (=) 16.3 15.9 0.0 (=) (=) (=)
Enforcement	0	0.03	0.08	0.12	0.12
5. High Gear Restriction	8 52.8 31.0 0.0 (4) (2) (0) 15.4 0.0 0.0 (1) (0) (0)	8 (=) 52.8 31.0 0.0 (=) (=) (=) 15.4 0.0 0.0 (=) (=) (=)	8 (=) 52.8 31.0 0.0 (=) (=) (=) 15.4 0.0 0.0 (=) (=) (=)	9 (+1) 26.8 45.8 0.0 (-2) (+1) (=) 16.1 0.0 0.0 (=) (=) (=)	9 (+1) 26.8 45.8 0.0 (-2) (+1) (=) 16.1 0.0 0.0 (=) (=) (=)
Enforcement	0	0	0	0.19	0.19
6. Low Gas Tax	8 44.9 35.4 0.0 (3) (2) (0) 17.3 17.4 0.0 (1) (1) (0)	9 (+1) 50.6 35.7 0.0 (=) (=) (=) 0.0 17.7 0.0 (-1) (=) (=)	9 (+1) 50.6 35.7 0.0 (=) (=) (=) 0.0 17.7 0.0 (-1) (=) (=)	9 (+1) 31.7 36.5 0.0 (-1) (=) (=) 18.0 17.5 0.0 (=) (=) (=)	9 (+1) 31.7 36.5 0.0 (-1) (=) (=) 18.0 17.5 0.0 (=) (=) (=)
Enforcement	0	0.01	0.01	0.28	0.28
7. High Gas Tax	10 53.3 18.9 0.0 (3) (1) (0) 0.0 17.9 0.0 (0) (1) (0)	10 (=) 53.3 18.9 0.0 (=) (=) (=) 0.0 17.9 0.0 (=) (=) (=)	10 (=) 53.3 18.9 0.0 (=) (=) (=) 0.0 17.9 0.0 (=) (=) (=)	11 (+1) 18.8 37.8 0.0 (-2) (+1) (=) 18.7 0.0 0.0 (+1) (-1) (=)	11 (+1) 18.8 37.8 0.0 (-2) (+1) (=) 18.7 0.0 0.0 (+1) (-1) (=)
Enforcement	0	0	0	0.26	0.26
8. Low Wage	8 34.4 29.3 0.0 (3) (2) (0) 14.5 15.1 0.0 (1) (1) (0)	9 (+1) 39.3 29.6 0.0 (=) (=) (=) 0.0 15.7 0.0 (-1) (=) (=)	9 (+1) 39.3 29.6 0.0 (=) (=) (=) 0.0 15.7 0.0 (-1) (=) (=)	10 (+2) 0.0 44.6 0.0 (-3) (+1) (=) 16.4 15.1 0.0 (=) (=) (=)	10 (+2) 0.0 44.6 0.0 (-3) (+1) (=) 16.4 15.1 0.0 (=) (=) (=)
Enforcement	0	0.02	0.02	0.33	0.33
9. High Wage	10 35.2 14.6 0.0 (3) (1) (0) 0.0 14.4 0.0 (0) (1) (0)	11 (+1) 36.3 15.4 0.0 (=) (=) (=) 0.0 0.0 0.0 (=) (-1) (=)	11 (+1) 38.4 0.0 0.0 (=) (-1) (=) 0.0 15.0 0.0 (=) (=) (=)	12 (+2) 0.0 30.1 0.0 (-3) (+1) (=) 15.4 0.0 0.0 (+1) (-1) (=)	12 (+2) 0.0 30.1 0.0 (-3) (+1) (=) 15.4 0.0 0.0 (+1) (-1) (=)
Enforcement	0	0.01	0.07	0.26	0.26
10. Low License Restriction	6 42.5 31.8 16.0 (3) (2) (1) 16.4 32.1 0.0 (1) (2) (0)	6 (=) 43.5 32.6 15.5 (=) (=) (=) 17.0 16.4 15.0 (=) (-1) (+1)	6 (=) 53.2 16.8 16.3 (+1) (-1) (=) 16.2 32.9 0.0 (=) (=) (=)	6 (=) 53.2 16.8 16.3 (+1) (-1) (=) 16.2 32.9 0.0 (=) (=) (=)	6 (=) 53.2 16.8 16.3 (+1) (-1) (=) 16.2 32.9 0.0 (=) (=) (=)
Enforcement	0	0.03	0.09	0.09	0.09
11. High License Restriction	11 39.4 19.1 0.0 (2) (1) (0) 0.0 18.0 0.0 (0) (1) (0)	11 (=) 20.6 19.3 0.0 (-1) (=) (=) 18.3 17.8 0.0 (+1) (=) (=)	11 (=) 40.4 0.0 16.7 (=) (-1) (+1) 0.0 18.1 0.0 (=) (=) (=)	11 (=) 40.4 0.0 16.7 (=) (-1) (+1) 0.0 18.1 0.0 (=) (=) (=)	11 (=) 40.4 0.0 16.7 (=) (-1) (+1) 0.0 18.1 0.0 (=) (=) (=)
Enforcement	0	0.02	0.1	0.1	0.1
12. Low Fine	5 48.0 31.3 16.0 (4) (2) (1) 16.1 32.0 0.0 (1) (2) (0)	6 (+1) 42.2 32.0 16.0 (-1) (=) (=) 16.4 32.1 0.0 (=) (=) (=)	6 (+1) 41.4 47.7 0.0 (-1) (+1) (-1) 16.9 16.5 15.4 (=) (-1) (+1)	6 (+1) 40.7 32.6 16.0 (-1) (=) (=) 16.8 32.3 0.0 (=) (=) (=)	6 (+1) 40.7 32.6 16.0 (-1) (=) (=) 16.8 32.3 0.0 (=) (=) (=)
Enforcement	0	0.03	0.06	0.16	0.16
13. High Fine	5 48.0 31.3 16.0 (4) (2) (1) 16.1 32.0 0.0 (1) (2) (0)	6 (+1) 42.2 32.0 16.0 (-1) (=) (=) 16.4 32.1 0.0 (=) (=) (=)	6 (+1) 41.4 47.7 0.0 (-1) (+1) (-1) 16.9 16.5 15.4 (=) (-1) (+1)	6 (+1) 41.4 47.7 0.0 (-1) (+1) (-1) 16.9 16.5 15.4 (=) (-1) (+1)	6 (+1) 41.4 47.7 0.0 (-1) (+1) (-1) 16.9 16.5 15.4 (=) (-1) (+1)
Enforcement	0	0.03	0.05	0.05	0.05

Figure 2

caused by MPAs at lower budgets, but it creates high ASL in site 1 and enough dispersal to sites 2 and 4 to induce spatial leakage of fishing effort to those dispersed-to sites from both the MPA and site 3. The redistribution of fishing effort creates an unfished site in site 3 and reduces fishing effort in site 5, which generates enough dispersal to site 6 to support fishing in that site despite distance costs. In this case, fishers that exit from the MPA site and leak their fishing labor to other fishing sites face higher distance costs to those new sites than to the MPA site (in site 1, closest to the village), which reduces total fishing labor because of the distance time costs and reduces incomes because of distance-based gas costs. In contrast, at high or unlimited budget constraints, the income-maximizing manager sites the MPA in the same site and causes one fisher to exit and become a wage specializer (figure 2, unlimited column), but chooses a (optimal) level of enforcement that does not deter all fishing in the MPA. Higher levels of enforcement would lead fishers to spatially leak their effort to other sites and to incur distance costs, which reduces income relative to illegal fishing in the MPA at the optimal low enforcement level.

Across all budgets, the income-maximizing MPAs create higher incomes and higher ASL than the open-access case because these MPAs deter overexploitation of fish sites to increase income, and all deterred fishing increases ASL. In contrast to ASL-maximizing MPAs, however, the income-maximizing manager chooses a lower level of enforcement than leads to complete deterrence in order to avoid deterring too much fishing or causing spatial leakage of fishing effort for income maximization (figure 2). Both managers consider the whole marinescape but are constrained to use an MPA in only one site, which limits the impact of the MPA on ASL and income. Income-maximizing MPAs always increase both ASL and incomes, but ASL-maximizing MPAs only create such win-win scenarios at enforcement levels low enough to improve incomes by deterring open-access overextraction.

ASPATIAL POLICIES

We consider five aspatial policies—a landing tax on all fish harvested, gear restrictions, onshore wage policies, a gas tax, and the number of fishing licenses—to determine how common fishery management and local development policies produce a spatial response in the presence of a spatial process (fish dispersal) and spatial decision (fisher site choice). See table 2 for the levels considered for each aspatial policy.

Reduction in fishing values. Both landing taxes and gear restrictions reduce the marginal net returns to fishing labor in every site, which in turn induces fishers to allocate less time to fishing overall and to exit from lower-valued sites (figures 1 and 2, no-MPA column). Although both

Figure 2. Income-Maximizing Manager's Optimal MPA with Aspatial Policies. Income-maximizing manager's optimal MPA siting and enforcement across enforcement budgets for different aspatial policy levels. The first column depicts the no-MPA distribution of fishers and effort. The total fishing labor in each site is displayed in each box (as a decimal). The number of villagers who choose not to fish is indicated by that number in the village location above the marinescape, with the change in that number from the no-MPA case in parentheses for each budget. The number of fishers in each site is identified in the marinescape figure for the no-MPA column in parentheses below the fishing effort, and changes in that number of fishers from the no-MPA baseline are indicated by the parenthetical =, +, and – values below the fishing effort for each MPA budget. The highlighted site is the optimal MPA site for the income-maximizing manager for each budget level. The last column depicts the percentage change in income and percentage change in stock that the MPA causes at each budget level; the black bar compares with the open access with no-MPA case (baseline row 1, no-MPA column) and the gray bar compares with the no-MPA outcome for that row's policy setting. See table 2 for aspatial policy levels.

Table 2. Aspatial Policy Levels

Description	Parameter	Baseline Value (Policy Range)	High Policy Level (% Above Baseline)	Low Policy Level (% Above Baseline)
Licenses	N	15 (1–9)	4 (–73.3%)	9 (–40%)
Wage rate for non-fishing labor	w	1.2 (1.4–2.2)	2.2 (83%)	1.8 (50%)
Catchability coefficient	$q_i, \forall i$	0.009 (0.008–0.003)	0.005 (44%)	0.007 (33%)
Gas price	p_g	0.2 (0.4–1)	1 (400%)	0.6 (200%)
Fine	F	1 (2–4)	0.8 (80%)	0.3 (30%)
Landing tax	τ_h	0 (0.1–0.4)	0.4 (40%)	0.2 (20%)

policies are aspatial, they can induce a spatial reaction from fishers because fishers move out of lower-valued sites, which are typically distant sites due to distance costs but dispersal can override the distance costs. Because the landing tax policies induce exit from fishing overall, fishers who remain in the marinescape exploit dispersal patterns that reflect fishers' new site choices; despite lower distance costs, fishers exit site 4 but do not all exit from more distant site 5 even at high taxes because they can capture the dispersal that site 1 receives from an unfished site 4; fishers exit the distant site 3 at high landing taxes to create a pattern that reflects distance's impact on value but also dispersal from unfished sites to other sites (figures 1 and 2, no-MPA column, rows 2 and 3; online appendix F). The distance aspects of the pattern of fishing are more prominent with gear restrictions—with no fishing in sites 3 and 6 at low restrictions and no fishing in sites 3, 5, and 6 with high restrictions—because the marginal value of dispersal is low enough that the extra dispersal does not offset the higher distance cost associated with fishing in site 5 (figures 1 and 2, no-MPA column, rows 4 and 5; online appendix I).

Distance-differentiated policies. Gas taxes and increased wage policies both increase the distance costs of fishing; gas taxes directly increase the costs of fishing, particularly in accessing distant sites, and wage-increasing policies increase the opportunity cost of fishing and of traveling to fishing sites. Both policies cause a reduction in fishing overall and in all sites because of the reduced fishing value but cause higher reductions far from the village as compared with the baseline. As fishers incur the gas tax as a cost, fishing income declines as fishers reduce their labor allocation to fishing. Total income can also decline if improved incomes from lower overextraction and increases in wage labor do not completely offset the loss in fishing net income. In the wage-increasing policy case, however, although fishing income falls, aggregate income (fishing income and wage income) always increases as compared with the no-policy setting because of the combination of the higher wage and higher labor allocation to wage labor. Again, for both gas taxes and wage increases, fishers first exit fishing in more distant sites, but also exploit dispersal patterns emerging from new fishing labor allocations following the aspatial policies; despite lower distance costs, fishers exit site 4 at high gas taxes and high wages but remain in more distant site 5 in order to capture the dispersal that site 1 receives from an unfished site 4 (figures 1 and 2, no-MPA column, rows 6–9; online appendices E and G). Still, these two aspatial policies increase distance costs, which leads to stronger spatial responses to the aspatial policies than with landing taxes and gear restrictions.

Restricting fishing with licenses. The number of licenses does not alter returns and distance costs directly, but restricting the number of fishers below the open-access level reduces open-access overextraction and generates rents on the marinescape through the steady-state stock effect. Here, open access is implicitly a level of 15 licenses, high license restriction considers 4 licenses, and low license restriction considers 9 licenses, while the unlicensed villagers conduct onshore wage labor. As the number of licenses increases from 1 (most restrictive license policy), licensed fishers spread out to low-distance-cost sites first, but exploit the dispersal benefit from site 4 by leaving it unfished at restrictive license levels at or below 6 (figures 1 and 2, no-MPA column, rows 10 and 11; online appendix H). License policies increase aggregate income by correcting the open-access problem, but with a highly restrictive level of licenses as with very few licenses, too few fishers on the marinescape leads to low aggregate incomes because fishing rents that are higher than wage work are not captured. Restricting licenses can improve aggregate income over open access and the fishers make spatial decisions within the marinescape, but marinescape-level license restrictions cannot specifically address incentives to overextract in particular sites, which implies that some sites may well face overexploitation as compared with a sole owner allocation of fishing effort (Townsend 1985).

MPAS IN THE PRESENCE OF ASPATIAL POLICIES

With most LMIC MPA managers constrained by a budget that limits enforcement and the amount of the marinescape in which to create MPAs, here we explore whether MPA managers within an exogenously determined aspatial policy setting can take advantage of the aspatial policies' impact on fisher decisions to achieve their goals. As above, the aspatial policies are exogenous and may increase or decrease income (see online appendix for income-maximizing levels of aspatial policies). All of the policies considered here reduce fishing effort across the marinescape and generate exit from fishing, thereby creating a different starting point for MPA decisions (figures 1 and 2, no-MPA column). The ASL-maximizing manager can achieve higher avoided stock losses at all budgets in settings with aspatial policies because of the aspatial policies' reduction in fishing labor (figure 3). The income-maximizing manager's MPA increases incomes over the policy baseline, but that baseline level of income may be lower than the no-policy case for policies other than wage and license policies (figure 4).

MPAs in policy settings that reduce fishing values. In the presence of landing taxes and gear restrictions, ASL managers use MPAs to achieve higher avoided stock losses at each budget than without these policies in place (figures 1 and 3). In contrast, because the aspatial policies reduce incomes, income-maximizing MPAs increase incomes over the policy setting without MPAs but cannot achieve the income levels of the MPAs without aspatial policies (figure 4). High enough gear restrictions and low/moderate budgets produce no income-increasing MPAs (figure 2, columns 2 and 3, low and moderate budgets, row 5). Given the lower fishing starting point, the MPAs are typically located in more distant sites at lower levels of the policy and at low and moderate budget levels, and in the nearest village site at higher levels of the policy or budget (figures 1 and 2). For high landing taxes at low/moderate budgets, both managers locate MPAs where they completely deter fishing in the MPA and create exit from fishing when possible. The managers differ at moderate budgets (3) for the low landing tax setting, with the ASL manager choosing complete deterrence of fishing in the

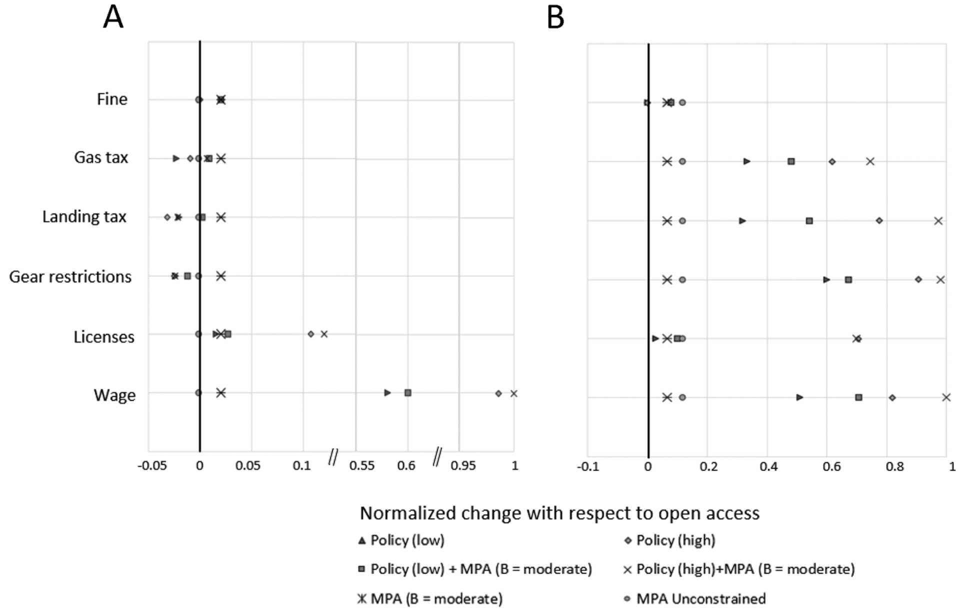


Figure 3. Economic and Ecological Impact of ASL-Maximizing MPAs. (A) Income. (B) ASL. Open access is represented by 0 on x-axis. Markers to the right (left) of this line represent a net gain (loss) in income or ASL for that policy as compared with open access. (No-ASL MPAs reduce ASL relative to open access for these ASL-maximizing MPAs.) The figure shows ASL and income responses to a high and low level of each aspatial policy, the ASL-maximizing manager's optimal MPA placement and enforcement level without the policy for an unconstrained case and a constrained case with a moderate enforcement budget (3), and the optimal MPA for an unconstrained and a constrained case for each policy level. The aspatial policy levels are the same as in figures 1 and 2. (Note scale gaps on x-axis.)

MPA while the income-maximizing MPA induces an income-improving spread of effort across sites. Similar to the no-policy setting, at high and unlimited budgets, the income-maximizing manager chooses enforcement levels that do not deter all fishing in the MPA in site 1 because additional enforcement either generates too much exit to improve incomes or generates spatial leakage of effort to more distant, and thus more costly and income-depressing, sites. The ASL-maximizing manager chooses such incomplete deterrence to prevent spatial leakage in settings with low landing taxes and high gear restrictions, but uses higher enforcement to generate exit from fishing in the other policy settings.

MPAs in distance-differentiated policy settings. In the presence of aspatial policies that alter distance costs (gas taxes and wage policies), the managers use the MPA location choice in coordination with the distance costs to deter fishing in the MPA. Because these policies make fishing at a distance relatively less attractive, managers can reduce fishing effort in, and induce exit from, MPAs sited in mid-distant sites at low and moderate budgets and rely on distance costs to limit spatial leakage of fishing to more distant sites (figures 1 and 2, columns 2 and 3, low and moderate budgets, rows 6–9). The distance-based policy settings therefore lead to a pattern of declining fishing labor across distance and more agglomerated fishing in sites near the village, until high enough budgets and aspatial policy levels lead to siting the MPA in site 1 (figures 1 and 2).

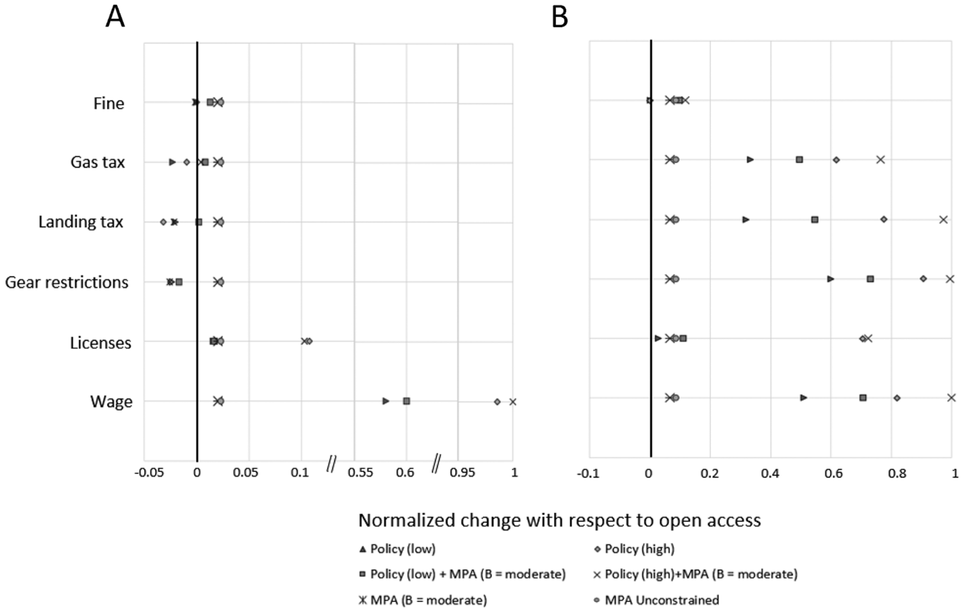


Figure 4. Economic and Ecological Impact of Income-Maximizing MPAs. (A) Income. (B) ASL. Open access is represented by 0 on x-axis. Markers to the right (left) of this line represent a net gain (loss) in income or ASL for that policy as compared with open access. (Income-maximizing MPAs can produce lower than open-access income levels because of the aspatial policies.) The figure shows ASL and income responses to a high and low level of each aspatial policy, the income-maximizing manager's optimal MPA placement and enforcement level without the policy for an unconstrained case and a constrained case with a moderate enforcement budget (3), and the optimal income-maximizing MPA for an unconstrained and a constrained case for each policy level. The aspatial policy levels are the same as in figures 1 and 2. (Note scale gaps on x-axis.)

MPAs in policy settings with restrictions on fishing licenses. Licenses address the overextraction tendency of open access, generating less extraction across the marinescape, including sites without resource rent dissipation. Still, licenses may not reduce overextraction in particular sites because the licenses are not site-specific. In the license cases, fishers and fishing effort agglomerate closest to the village and create low stock levels there (online appendix H, figure H5). The high license restriction increases incomes relative to the baseline more than the low license restriction because the high license restriction brings the number of fishers closer to the income-maximizing number of fishers in the marinescape and solves more of the open-access overextraction problem (online appendix H, figure H4). In the no-policy case (figure 1, row 1), the MPA induces exit of one fisher, which creates the same number of fishers as the license level of 9 (figures 1 and 2, row 10). In the license aspatial policy setting, however, the MPA does not need to induce that exit. Both managers' MPAs cannot induce further exit from fishing because fishers choose other sites—leak their effort—in response to MPA enforcement rather than exit. For the ASL manager, the location choice centers on sites in which the enforcement budget can reduce fishing in the MPA (figure 1, rows 10 and 11). With high license restrictions, the ASL manager focuses on MPA locations and enforcement levels that limit the spatial leakage of effort. In contrast, the income-maximizing manager positions the MPA to use enforcement and dispersal to spread fishers out to reduce overextraction in low-distance sites. Because license restrictions discourage excess fishing, the income-maximizing manager achieves the unconstrained optimal MPA and enforcement with a moderate budget.

Fines as an additional tool. Although fines as a penalty for fishing in the MPA are not an aspatial policy on their own, adding that penalty to the penalty of losing the costs and fish harvested creates a larger response to MPAs at each enforcement level. A fine generates lower levels of fishing effort, exit from the MPA site, and complete deterrence of fishing in the MPA at lower levels of enforcement than the no-fine case (figures 1 and 2, rows 12 and 13). Because the fine does not alter fishing incentives beyond the MPA, it does not typically create additional exit from fishing but instead generates more spatial reallocation of fishing labor—spatial leakage—to non-MPA sites to capture MPA-induced dispersal.

Synthesizing results: What should MPA decisions consider? Dispersal, fishery exit, distance costs, and spatial leakage. Without control over the entire marinescape and with limited budgets, MPA managers can strategically use MPA location and enforcement-level decisions to influence fisher decisions at the extensive margin (including both exit from fishing to become a wage specializer and spatially reallocating or leaking fishing effort to another site) and at the intensive margin (including increased fishing effort due to fish dispersal from the MPA to other sites). First, in general, because of discrete distance costs, MPAs that induce exit from the entire fishery produce the highest ASL response, with lower required enforcement levels to induce exit in more distant sites because of fishers facing distance costs. Second, incomplete deterrence is necessary at some budget levels, is optimal for the income-maximizing MPAs beyond the level that deters open-access overextraction, and is optimal for both managers to prevent ASL- or income-reducing spatial leakage of fishing effort. Third, an MPA with enough enforcement becomes a policy-driven source of dispersal to increase resource rents elsewhere, which increases fishing effort levels at the intensive margin and supports leakage of effort to other sites at the extensive margin. The ASL manager leverages that dispersal by choosing MPA sites that create dispersal to more distant sites, which reduces fishing and increases ASL. In contrast, the income-maximizing MPA manager aims to reduce income-diminishing open-access overextraction and uses MPA siting and enforcement to create dispersal to less distant sites to increase incomes by reducing distance costs and spreading fishers out to avoid sites with overextraction. When MPAs are small relative to the ecological and economic system, they have limited impact due to the open-access fishing across the non-MPA marinescape, which makes consideration of the impact of the MPA on non-MPA sites due to leakage and dispersal critical to MPA decisions. While many economic analyses and PA siting software assume complete enforcement or complete deterrence and do not include fisher location decisions, MPA managers that consider spatial leakage and incomplete deterrence in designing MPAs can achieve higher income or ASL goals per budget.

Do MPAs create ecological-economic win-win scenarios or an economic burden? Whether the ASL-maximizing MPA creates a win-win situation or an income burden depends on the type and level of aspatial policy on the landscape (figures 1 and 3). In settings with wage improvements and license restrictions, ASL-maximizing MPAs lead to increases in both the ASL and incomes, while adding an ASL-maximizing MPA to the marinescape managed with three licenses—which maximizes income—leads to a decline in income (online appendix H, figure H1). When the aspatial policy level is too low to correct open-access outcomes, the ASL-maximizing MPAs can improve incomes at some budget levels and potentially offset the policy setting's income losses; here, in low license restriction and high gas taxes cases with high MPA enforcement and in low license restriction cases at moderate and high enforcement budgets. When the aspatial policy level leaves little open-access overextraction, the ASL-maximizing MPA causes income declines, here in high gear restriction, low license restriction, and high gas tax policy settings—although high and unlimited enforcement budgets lead to increased income in the high gas tax case (figures 1 and 3). In general, ASL-maximizing MPAs do not impose an income burden on the community unless open-access overextraction is low or enforcement is high enough to cause income-reducing decreases in fishing.[6] Even at high levels of enforcement, employing ASL-maximizing MPAs in settings with aspatial policies that improve wages or strongly restrict fishing licenses can lead to win-win situations of both ecological (ASL) and economic (income) outcomes.

The income-maximizing MPAs increase incomes in all policy settings and partially offset income losses associated with policies other than wage and license policies, thereby creating no income burden beyond that imposed by the policy setting (figure 4). They generally provide win-wins with both income improvements and higher ASL (figures 2 and 4). However, income-maximizing MPAs can induce fishing effort leakage that reduces ASL; for example, with low license restrictions and a low budget, the income-maximizing MPA causes effort to leak to sites where they generate net ASL losses (figure 2, low licenses) and a trade-off between income and ASL.

Do aspatial policies augment MPA outcomes? Because each policy here reduces fishing effort and increases ASL, these policy settings increase the ASL level that the ASL-maximizing manager achieves with their MPA at every budget. These policies work in concert and, taken together, the policy settings and ASL MPAs generate higher levels of ASL than the no aspatial policy MPAs (figure 3). Similarly, because the wage and license restriction policy settings increase income, the income-maximizing MPAs reach higher levels of income at each budget than the no-policy setting MPAs (figure 4). In contrast, because the other policies themselves can reduce incomes, the income-maximizing MPAs are unable to generate net income gains at the levels achievable without the policies. Yet, income-maximizing MPAs in aspatial policy settings lead to higher ASL than the income-maximizing MPA without the aspatial policy. Because the aspatial policies induce exit from fishing, both managers can use lower levels of enforcement per site to induce exit from fishing altogether or to deter fishing in the MPA. The distance-based policies—wage and gas taxes—reduce the necessary enforcement spending in more distant sites to generate ASL gains, further increasing the impact of MPAs per budget. The distance-based policies also enable ASL-maximizing managers to avoid ASL-reducing spatial leakage of fishing effort to more distant sites.

STYLIZED CASE EXAMPLES

To further explore how this framework addresses coastal management decisions in LMICs, we present policy decisions for two marinescapes that we parameterize to match the salient characteristics of the settings, including borders and reefs: the MPA expansion decision for Costa Rica's Caribbean coast; and policies to induce poverty alleviation in Tanzania's marine parks.

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[6] A setting with no onshore wage creates the lowest possible stock level in open access (online appendix C).

Costa Rica. In this section, we adapt our model to represent the artisanal fishery bordering Tortuguero National Park (TNP) in Costa Rica to address that country's decision about expanding MPAs (SINAC 2012), here stylized as a question of whether, and if so where, to expand TNP by one additional MPA site. This marinescape is characterized by open borders for fish dispersal; TNP with high fish stocks outside the border near (south of) the town of Tortuguero, and Nicaragua's open-access fishery on the other (northern) border (figure 5; online appendix A). TNP has become a popular tourist destination for turtle and other wildlife viewing, which generates high onshore wages that have pulled fishers out of fishing (Madrigal-Ballestero et al. 2017). In addition, fishers face high fines if they are caught fishing illegally in TNP. To address these characteristics, we define a Costa Rican baseline marinescape with open borders to fish dispersal with high stocks outside of the marinescape on one side (marked with a + in figure 5) and low stocks on the other border (marked with a –), which alters dispersal of fish (online appendix A); a fine in addition to the loss of time and harvest used above (table 1); and a baseline wage higher than that in the rest of this paper (table 1), which we also modify to a moderate (15% higher than this case's baseline) and a high (17% higher) onshore wage to depict ongoing increases in that wage and its impact on fishing (figure 5, baseline, moderate wage, and high wage rows for both managers).

In this baseline Costa Rica example, the high opportunity cost of time induces five fishers to become wage specializers, and the dispersal from TNP focuses fishing effort in near-village locations, as observed near TNP (Madrigal-Ballestero et al. 2017; here, figure 5). The wage level interacts with the enforcement budget and dispersal—in this case example, dispersal from the TNP outside the marinescape enters sites 1 and 4 (figure 5)—to determine the optimal location for extending the MPA. The ASL-maximizing manager emphasizes deterrence from fishing within the MPA with MPAs in middle distance sites and emphasizes exit from fishing less than in other settings because fishers who leak effort to site 1 impose little ASL cost on the system because of dispersal into site 1 from TNP. When the onshore wage and budget are high enough (here moderate budgets and above), the optimal ASL-maximizing MPA is in site 1 contiguous to TNP and nearshore, which induces more exit from fishing and wage specialization overall and deters fishing in the MPA, but creates some spatial leakage with fishers "fishing the line" near TNP and the new MPA. Still, the high wage and dispersal out of the fishery on the right-hand side of the marinescape discourage spatial leakage of effort to further sites. Taking advantage of the in-dispersal from TNP, the income-maximizing MPA manager locates the new MPA adjacent to the TNP in sites 1 or 4 at moderate wages and in site 1 for high wages, which induces exit from fishing overall but often does not deter all fishing in the MPA because higher enforcement reduces incomes through distance costs of spatial leakage (figure 5, rows 8 and 9). Overall, higher wage levels enable both ASL- and income-maximizing MPA managers to achieve their goals at lower enforcement budgets and create situations in which enforcement levels that permit illegal extraction within the MPA are often optimal for income-maximizing MPA managers, as above.

As predicted by theory, for any particular MPA location, the enforcement level employed declines with an increasing fine level because the fine reduces the expected income from fishing in that site, which implies that the manager achieves the optimal outcome at a lower budget (Sutinen and Andersen 1985; Hallwood 2004; here, figure 5). For both managers, high fines mean that lower enforcement levels are necessary to achieve the same impact as MPAs without fines. In addition, the income-maximizing manager can achieve their budget-unconstrained MPA site and

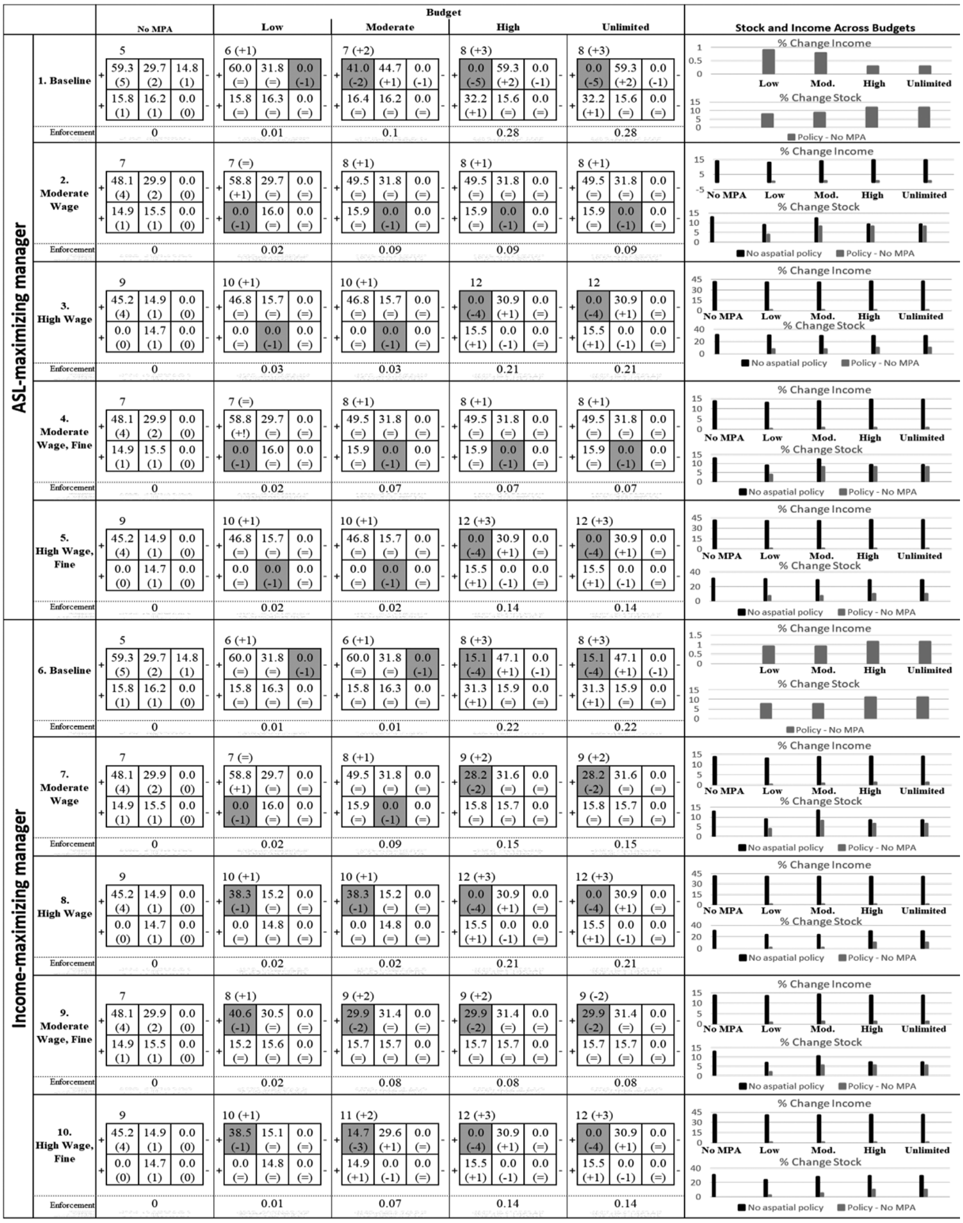

Figure 5. ASL- and Income-Maximizing MPAs for Costa Rica Case Example. ASL- and income-maximizing managers' optimal MPA for different onshore wage and fine levels. TNP (+) indicates that the MPA outside the marinescape is a source of fish, while the low fish population near Nicaragua (–) serves as a sink of fish, causing dispersal into the marinescape on the left border and out of marinescape on the right border. Costa Rica is characterized by high wage (17% above the paper's baseline) and a fine (of 1). The moderate wage is 14% higher, and the high wage is 29% higher, than the Costa Rica baseline. The fine is 300% above the Costa Rica baseline fine. The black income and stock bars compare with the baseline case (across rows), and the gray bars compare with that policy's no-MPA outcome in the no-MPA column (across columns). The total fishing labor in each site is displayed in each box (as a decimal). The number of villagers who do not fish is indicated by that number in the village location on the marinescape, with the change in that number from the no-MPA case in parentheses for each budget. The number of fishers in each site is identified in the marinescape figure for the no-MPA column in parentheses below the fishing effort, and changes in that number of fishers from the no-MPA baseline are indicated by the parenthetical =, +, and – values below the fishing effort for each MPA budget.

outcomes at lower budgets in the presence of fines. For example, with a moderate wage and no fine, the manager sites the MPA in site 4, but with a high fine, the manager sites the MPA in site 1 and achieves their budget-unconstrained baseline outcome. The fine influences the optimal MPA location and the enforcement level and makes the enforcement level more effective because the fine increases the cost of fishing within the MPA; higher fines imply lower levels of enforcement in a given location.

In this stylized case example and as observed in Costa Rica, high onshore wages induce wage work and fishing exit and influence the pattern of fishing to focus fishing in nearshore locations, which receive dispersal from the existing TNP. With a high enough onshore wage and enforcement budget, extending TNP close to the village with moderate enforcement levels improves both incomes and marinescape stocks. The use of fines in combination with MPA enforcement induces stronger ASL and income responses from MPAs at lower enforcement budgets.

Tanzania. The gazetting legislation for Tanzania's marine parks requires these MPAs to improve biodiversity and fish stocks while providing poverty alleviation to within-MPA villages (MIMP 2011; MNRT 2005; Robinson, Albers, and Kirama 2014). Both Mnazi Bay Ruvuma Estuary Marine Park (MBREMP) and Mafia Island Marine Park (MIMP) restrict fishing within the park to local villagers, which we mimic here by a limit on the number of fishing licenses. In the absence of tourism markets for wage increases, MIMP provides direct income payments without a labor commitment to villagers based on park entry fees, while MBREMP provides alternative livelihood projects that require labor time commitments and cause "conservation by distraction," as villagers have less time to allocate to fishing. We model both methods of poverty alleviation by providing a payment both without (MIMP) and with (MBREMP) a reduction in total labor time available. To further relate to the conservation economics literature, we explore payments that are conditional on cooperation with MPA restrictions by imposing an additional penalty of losing the payment if caught fishing in the MPA. To characterize the Tanzanian setting, we also include a high fish carrying capacity reef in site 5, which leads to high levels of fishing effort in that site (figure 6, demarcated with dotted boundaries). For this case example, limiting fishing to villagers within the park, mimicked here by reducing licenses to 6 from 15, increases both marinescape stock and aggregate income by reducing overfishing (see figure 6, row 2, black bars for vs. 15 licenses), and we use that level of licenses as the aspatial policy base case (no-MPA column) for the payment policies (see figure 6, bars for policy–no MPA). Adding MIMP-style direct payments without a work requirement leads to increases in income but does not alter the ASL because the lump sum payment does not influence marginal labor allocation decisions (figure 6, comparing across the no-MPA columns). Tying income payments to a commitment of labor time does not cause any additional exit from fishing but does increase ASL by reducing total fishing labor in the marinescape, as fishers have less time to devote to both fishing and onshore wage labor. Conditional-on-MPA cooperation income payments increase incomes as compared with the no income payment baseline but produce lower incomes than unconditional payments because linking payments to the MPA regulations acts like a fine on fishing in the MPA.

The license restriction reduces fishing effort enough that the ASL-maximizing MPAs do not create additional exit and no MPAs can increase incomes beyond the six-license baseline. In the presence of income payments without labor commitments, the ASL-maximizing manager locates the MPA at a low budget to induce exit from fishing in site 3, either by directly placing the

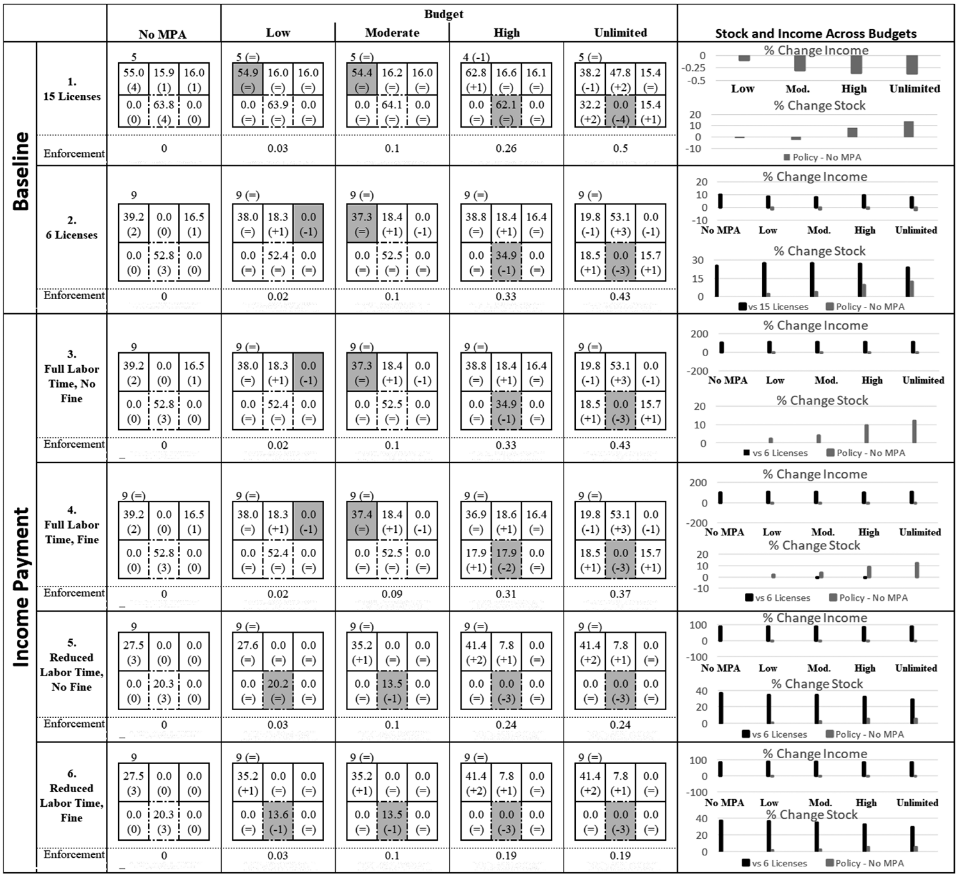

Figure 6. ASL-Maximizing MPAs for Tanzania Case Example. ASL-maximizing manager's optimal no-take zone (shaded gray) for different policy settings across budgets. In Tanzania, the entire marinescape is an MPA that permits fishing by licensed fishers, but no-take zones are established to protect particular sites in the MPA. The six-license case forms the baseline for the four income payment cases. The rows with "reduced labor time" reflect the settings in which the payment requires using some labor for non-fishing activities. The cases of "no fine" are cases in which the income payment is not conditional on cooperation with the no-take zones. The cases of "fine" are cases in which the income payment is lost if the fisher is caught fishing in the no-take zone; that conditionality of the payment behaves like a fine set to the level of the income payment. To mimic the reefs in this marinescape, site 5 is characterized by a higher carrying capacity. The black income and stock bars compare with a license baseline (across rows), and the gray bars compare with that policy's no-MPA outcome in the first column (across columns). The total fishing labor in each site is displayed in each box (as a decimal). The number of villagers who choose not to fish is indicated by that number in the village location on the marinescape, with the change in that number from the no-MPA case in parentheses for each budget. The number of fishers in each site is identified in the marinescape figure for the no-MPA column in parentheses below the fishing effort, and changes in that number of fishers from the no-MPA baseline are indicated by the parenthetical =, +, and – values below the fishing effort for each MPA budget.

MPA in that site or by placing the MPA in site 1, which creates enough dispersal in site 2 that the fisher in site 3 relocates (figure 6). At high and unlimited budgets, the manager places the MPA in site 5—the reef, which creates dispersal to neighboring sites—and enforces it to cause exit from the MPA at unlimited budgets but cannot induce exit from fishing and instead induces spatial leakage of effort. The MPA with payments conditional on MPA cooperation ("with fine" in figure 6) has lower levels of fishing effort than those without conditionality until unconstrained budgets, which generates spatial leakage of effort to reef/MPA-neighboring sites. Making the income payments conditional on MPA cooperation enables the ASL manager to achieve their goals using less enforcement than with unconditional payments; for example, the MPA achieves complete deterrence from fishing in site 5 at lower levels of enforcement when the payments are conditional on compliance with the MPA (figure 6, row 3 compared with row 4 and row 5 compared with row 6). Because income payments tied to labor requirements reduce total fishing effort in the marinescape, the ASL manager always protects the reef, site 5, and fully enforces the MPA at unlimited budgets, which induces a higher concentration of fishing effort near the village through spatial leakage of effort rather than through exit from fishing (figure 6, rows 5 and 6).

Achieving Tanzania's dual goals of ecological and economic improvements through MPAs can work through control of the number of fishers and conditionality of payments on cooperation with no-take zones or with labor commitments. In practice, MBREMP is less effective than MIMP in limiting fishing to in-park villagers (Robinson, Albers, and Kirama 2014). MBREMP villagers report undertaking less fishing because of income-generating projects, implying conservation by distraction, although these reports come from people who are less reliant on fishing. Just as many conservation-development programs fail to integrate conservation and development, neither Tanzanian marine park uses their projects or payments to create an incentive for conservation (Bauch, Sills, and Pattanayak 2014). These results demonstrate that linking the penalty for illegal fishing to access to the payment or project could induce conservation MPAs, even at low enforcement budgets, while providing poverty alleviation.

DISCUSSION

How can MPAs and aspatial policies address both income and ASL goals? The Sustainable Development Goals include both increasing area in marine protected areas and achieving poverty alleviation, although these goals can conflict in many settings. This analysis identifies mechanisms through which MPAs alter community income and increase marine conservation. Because aspatial policies induce reductions in fishing effort, such policies augment the avoided stock loss (ASL) levels achievable by small ASL-maximizing MPAs at all budgets. ASL-maximizing MPAs generate ecological and economic win-win scenarios in cases where the MPA resolves some of the income-depressing open-access overextraction, but they can reduce community incomes in cases where the enforcement budget is high enough to deter fishing that is more profitable than wage work. In those cases, income gains from aspatial policies like wage programs and license restrictions can offset some or all of the MPA-induced income loss to achieve win-win outcomes. Income-maximizing MPAs typically generate both income and ASL gains, do not create income burdens on local communities, and can offset some of the income losses from tax and gear restriction policies. Some empirical literature depicts a positive impact of protected areas on nearby population incomes, as evidenced by increased wages (e.g., Robalino and Villalobos 2015), but those increased wages may accrue to in-migrants rather than to local residents. In such a situation, local residents may bear a burden of the PA that is masked by the wage increases, and local resource extractors may not be incentivized by the wages to reduce labor allocation to that activity and provide conservation benefits. Therefore, understanding the mechanisms by which protected areas change local resource extractors' behavior and opportunities is critical for evaluating the likely impact of MPA expansions on both local incomes and conservation goals.

In the Costa Rica setting, tourism has driven high wages in the labor market that has had a positive impact on both incomes and fish stock conservation, operating through fisher incentives to reduce fishing effort and increase wage labor (Madrigal-Ballestero et al. 2017). Still, aspatial and MPA policies that correct overextraction open-access problems can lead to decreases in onshore wages as labor exits fishing and enters onshore labor markets (Manning, Taylor, and Wilen 2018; Scott 1957; Wilen 2013). However, these effects may disappear in the long run and depend on the structure of the labor market (Baland and Bjorvatn 2013; Manning, Taylor, and Wilen 2014). In the case of Tortuguero National Park, the analysis here suggests that expansion close to the town of Tortuguero would have the most impact, but that impact relies on the expansion creating high enough wages to induce further exit from fishing in a region that has already witnessed large levels of such exit. Ongoing work explores a fuller model that endogenizes onshore wage to the level of labor in that market from fishery exit and in-migration. In the case of Tanzania's marine parks and reflecting stakeholder comments, this analysis suggests that enforcing the restrictions on fishing by non-park residents could improve both rural incomes and conservation outcomes. In addition, linking park entry fee-based payments to conservation actions rather than using lump payments would also achieve the dual goals of poverty alleviation and conservation. Beyond these specific examples, establishing MPAs to increase both ASL and incomes requires understanding the labor allocation response of current resource users within their market and policy settings and creating policies that induce conservation by incentivizing non-resource-based activities.

Using this framework to inform MPA siting and empirical analysis. As in ecosystem-based modeling, the necessary data to site MPAs or evaluate their impact includes information about the policy setting, fisher decisions, and market functions in addition to ecological data such as stock assessments. Empirical analysis of MPAs could use the model mechanisms explored here to understand how the MPA creates impact and to determine data needs to improve that impact. For siting MPAs, this framework suggests the importance of data that describe the wage levels that can pull fishers out of fishing and the distance costs that contribute to fishers' selection of sites. For example, in comparison to triage-based MPA siting decisions that site MPAs in the locations of highest extraction, MPA siting based on how fishers respond to the MPA, based on labor market and distance cost information, could produce larger impact on ASL and income from MPAs sited at higher distances despite lower pre-MPA fishing effort there. Rules of thumb for siting income-maximizing MPAs include using the location and enforcement level to induce exit overall and exit from highly extracted sites, often using dispersal from the MPA to spread fishers out to reduce open-access overextraction. Rules of thumb for siting ASL-maximizing MPAs include creating exit from fishing and using the MPA location and enforcement level to increase distance costs that reduce fishing effort and spatial leakage of remaining effort.

Our framework also informs MPA impact analysis, which typically uses methods like propensity score matching to quantify the degree of additional resource abundance the protected area produces. These analyses rarely explore management aspects of protected areas, such as enforcement levels or de facto resource restrictions rather than de jure rules. Moreover, they typically consider siting decisions with simple distance measures, which limits their ability to inform siting and management decisions for other protected areas (e.g., Andam et al. 2008; Pfaff et al. 2014). Incorporating the insights of our framework would generate more information about how the local economic conditions, PA siting, and PA management combine to generate effective conservation. In addition, these analyses typically assume a fixed distance buffer for PA impacts, in order to define appropriate comparators; this article emphasizes the necessary criteria for defining such a buffer, given that the spatial range of impact is a function of the scale of both fish dispersal and fishers' decisions. In addition, MPA impact analysis requires data and assessments across the marinescape rather than solely within the MPA because ignoring fishers' spatial leakage to other marinescape sites overstates the marinescape impact of the MPA.

In the absence of pre- and post-MPA data, MPA impact analysis for incomes could include assessments of whether fishing effort has moved to onshore opportunities, whether open-access overextraction has been reduced, and whether fishing effort has moved to more costly distant sites with negative impact on incomes. MPA impact analysis for marinescape ASL could examine whether the MPA has created dispersal of fish and the fisher response to that dispersal. For example, if fishers "fish the line" evenly all around the MPA, the MPA's location is not creating distance costs that limit spatial leakage of effort that offsets MPA gains. In addition, this framework implies testable hypotheses for the impact of MPAs across many settings, including whether aspatial policies reduce fishing effort enough to make MPAs more effective at a given enforcement budget and in proximity to fishing ports. Using the modeling mechanisms described here can improve MPA siting decisions and interpretation of empirical MPA impact analysis.

Relationship to the resource and conservation economics literature. This paper extends the conservation economics literature in several ways. First, because this analysis centers on the micro-foundations of fisher decisions rather than solving for a particular equilibrium condition, the analysis considers a spectrum of policy settings rather than the end points of unmanaged and perfectly managed artisanal fishery settings. Second, modeling distance costs in each fisher's decision rather than as a fixed cost per site facing total fishing effort provides insight into how the MPA location decision can leverage distance costs and fish dispersal to alter fishing choices at the extensive and intensive margins, and to create exit from fishing. Third, although the law and economics literature finds that costly enforcement implies an optimal level of enforcement that does not deter all illegal activities, many conservation economic frameworks assume costless enforcement and complete deterrence. Here, we include enforcement costs and budget constraints common in LMIC settings and find cases in which MPAs do not deter all illegal fishing due to budget constraints or to avoid the spatial leakage of effort and distance costs' impact on marinescape incomes and ASL.

CONCLUSION

This paper analyzes the potential for complementarities between spatial and aspatial policies to manage open-access fisheries in low- and middle-income countries. Where regulatory capacity limits the size and enforcement of marine protected areas, policy makers may not meet their goals in isolation, but combining spatially explicit siting of MPAs with aspatial policies can improve both ecological and economic outcomes. Aspatial policies that disincentivize fishing effort can enhance an MPA's ability to prevent depletion of steady-state fish stocks. Aspatial policies that specifically target the cost of traveling to fishing sites (e.g., fuel taxes, onshore wage subsidies) can generate additional ecological gains by mitigating MPA-induced spatial leakage of fishing effort to more distant fishing sites. When the goal of the MPA is to increase incomes in artisanal fishing communities, complementary onshore wage policies and license restrictions can help an MPA achieve this goal, while also generating ecological benefits. When the goal of the MPA is ecological, aspatial wage policies can help to protect against the burden of lost fishing income from reduced access to fishing in the MPA.

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