Optimal Siting, Sizing, and Enforcement of Marine Protected Areas

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Abstract
The economic empirical analysis assessing the effectiveness of parks uses predictions of threats to resources to determine "avoided deforestation" yet such predictions are not commonly used in determining the siting and management of parks in order to maximize their effectiveness. Especially in cases of incomplete enforcement that are abundant in lower income countries, the reaction of potential resource extractors determines both the conservation and economic outcomes from protected areas (PAs). Agents may respond either by shifting extraction to areas outside the PA or by illegally extracting within an incompletely enforced PA. In designing PAs, it is crucial to consider how both types of response will alter outcomes under the PA policy and use those outcomes to define optimal PAs. Our model analyzes how a manager designs a PA (MPA) to achieve either conservation or economic goals by incorporating fishers' spatial equilibrium response to the policy. We incorporate three salient features of (M)PA policies in developing countries -- spatially explicit travel costs; wage labor as an outside option with diminishing marginal returns; and incomplete enforcement -- each of which is essential to characterize the interplay between (M)PA policy design and fishers' equilibrium response to the policy. Using a spatially-explicit bio-economic model of fish dispersal and fisher location and labor allocation decisions resulting in a spatial Nash equilibrium, this paper demonstrates how the optimal size, enforcement, and location for a marine protected area (MPA) and the resulting effectiveness of the MPA depend critically on the optimization and equilibrium response of fishers. This analysis shows that optimal MPAs differ markedly across goals and across enforcement budget levels; that illegal harvest in MPAs can be optimal, especially when small levels of enforcement solve some of the open access over-extraction problem; and that fish dispersal and fishers' location decisions interact with MPA policies to have marinescape-wide implications including leakage. The analysis characterizes the costly mistakes generated by failing to incorporate the re-optimization of fishers in response to the MPA and incomplete enforcement when making MPA siting and enforcement decisions. Overall, this paper defines the microfoundations of fishers' location and labor decisions, and uses those to determine the most effective size, configuration, and enforcement of MPA networks.

Keywords: Marine protected areas; spatial; Nash equilibrium; bio-economic model; fisheries; development; no-take zones; marine reserves; enforcement; leakage; systematic conservation planning; additionality; park effectiveness; reserve site selection

I. Introduction

The Convention on Biodiversity obliges its signatory countries to expand terrestrial and marine protected area to 20 percent of coastal and land area (Pereira et al., 2013). The ecological and economic outcomes from Protected Area (PA) siting and management are a function of how people, as potential PA resource users, respond to the PA and its management. For example, a park without enforcement becomes a "paper park" when people continue to use the resources or land within the PA due to a lack of disincentive for that use. Economic efficiency requires that siting and management decisions reflect that response. Because many low income country PAs face low budgets for enforcement to create disincentives for ongoing resource use, PA decisions made without reflecting the response of resource users to both the PA and its level of enforcement do not correspond to economically efficient PA choices. The empirical economic analysis of park effectiveness uses von Thunen-inspired models to predict a level of deforestation that would occur if a location was not in a protected area, and then calculate the level of "avoided deforestation" or additionality created by the park as a measure of the park's effectiveness (e.g. Pfaff, et al. 2014). Working from the opposite starting point, this paper uses a model of fishers' location and effort decisions to predict the reaction of fishers to a Marine Protected Area (MPA), and uses that reaction to determine the optimal size, site, and enforcement level of a MPA to maximize avoided fish stock loss and other objectives.

Providing the spatially explicit micro-foundations of fisher spatial decisions called for in Sanchirico and Wilen (2001), this paper develops and employs a model of individual fishers making optimal fishing site and labor effort decisions that result in a spatial Nash equilibrium for the group of fishers. Extensive stakeholder interviews in Tanzania and Costa Rica provide stylized facts about the impact of distance costs on artisanal fishers' site choices and the impact of enforcement costs and limited budgets on managers' MPA size, site, and enforcement decisions. Fishing sites are homogeneous in biology with density dispersal across sites but the model incorporates heterogeneity in distance costs to various fishing sites. Reflecting a low income country setting, MPA managers facing costly enforcement aim to achieve one of several goals for the MPA within a marinescape – maximize yield, income, avoided aggregate fish stock loss, or avoided MPA fish stock loss – subject to budget constraints, fish dispersal, and the reaction of villagers. Given distance costs and fish dispersal, fishers' best-response functions depend on both the spatial configuration of the MPA and the manager's level of enforcement, which allows fishing effort in the system to respond to specific policy parameters and the onshore wage. The optimal MPA choice reflects the spatial Nash equilibrium of fisher behavior at the long run steady state fish stock.

The main contribution of this paper is its determination of optimal MPA size, site, and enforcement levels as a function of fishers' spatial equilibrium responses to the MPA and the bioeconomic setting. That contribution extends the economic analysis of MPAs by including multiple sites and spatially explicit modeling of fisher decisions with heterogeneous distance costs and incomplete enforcement. Similarly, this analysis extends the systematic conservation planning and reserve site selection literatures by including a model of fishers' "threat" to resources directly in the decision framework for selecting MPA sites. The results also reveal qualitative and quantitative differences in optimal MPAs established to achieve different goals; show changes in MPA siting across budget levels; elucidate the complicated relationships between enforcement's creation of a probability of illegal fishers losing their harvest and MPA outcomes; and inform a policy discussion

II. Model

Overview

We use a spatial bio-economic model to study the MPA manager's siting, sizing, and enforcement level decisions. First, we define our stylized spatial setting as a $R \times C$ matrix with a village located next to the first cell (Figure 1). The biological part of the model is a fish metapopulation structure with density dispersal. The economic part of the model includes two types of participants: Villagers and one manager. The villagers allocate labor across onshore labor for wage and fishing labor to maximize income. Each villager considers other villagers' choices and chooses where (one site) and how much to fish, which results in a spatial Nash equilibrium in fishing locations and effort. Finally, the manager considers both the fish dynamics and the villagers' equilibrium response to the biological and policy setting to choose the sites, size, and enforcement level of the MPA to maximize its goal.

[FIGURE 1]

Fish dynamics

In common with much of the marine economics literature, a fish metapopulation structure on a marinescape represented by a $R \times C$ matrix with density dispersal defines the biological and spatial setting. A fishing site i is one cell in that matrix, indexed from 1 $to\ R \times C$. Sites in the first row, $i \in \{1, \dots, C\}$, are closest to the shore (see Figure 1).

Fish net growth, harvest, and dispersal over time change the fish stock in each site as follows:

$$\boldsymbol{X_{t+1}} = \boldsymbol{X_t} + G(\boldsymbol{X_t}, \boldsymbol{K}) + \boldsymbol{D}\boldsymbol{X_t} - \boldsymbol{H_t}\,,$$

where $\boldsymbol{X_t}$ is a $(R \cdot C) \times 1$ vector of fish stocks over fishing sites x_i at time t, $\boldsymbol{K}$ is a $(R \cdot C) \times 1$ vector of site carrying capacities, $\boldsymbol{D}$ is a $(R \cdot C) \times (R \cdot C)$ dispersal matrix, and $\boldsymbol{H_t}$ is a

$(R \cdot C) \times 1$ vector of all fishers' harvest from each site i at time t. The logistic function $G(\boldsymbol{X_t}, \boldsymbol{K}) = g\boldsymbol{X_t}\left(1 - \frac{\boldsymbol{X_t}}{\boldsymbol{K}}\right)$ depicts natural population net growth at each specific site, with g indicating the intrinsic net growth rate. The dispersal matrix $\boldsymbol{D}$ operationalizes the density dependent dispersal process as a linear function of fish stocks densities of all sites with net dispersal to lower density neighbors that share a boundary through rook contiguity (Sanchirico and Wilen 2001; Albers, et al., 2015). Our results hold in the steady state stock of fish, $\boldsymbol{X_{SS}}$, which occurs when $\boldsymbol{X_t} = \boldsymbol{X_{t+1}}$.

Villagers

We include one village with N identical villagers. Each villager n seeks to maximize income from two sources: fishing for fish harvest income and onshore labor for a wage. To achieve this goal, the villager chooses how much time to work on shore and, if he chooses to fish, where to fish and how much time to fish. In making this decision, any given villager recognizes that he has a fixed amount of labor time to spend (L); thus, the time he spends working onshore (l_w), fishing in a given site (l_{fi}), and traveling in his boat from the village to the fishing site (l_{di}) is constrained:

$$L \geq l_w + l_{fi} + l_{di}.$$

The different distances from the village to each fishing site and the fish dispersal introduce two types of spatial heterogeneity that drives differences in fishing sites in our model from those in spatially homogeneous frameworks, such as Sanchirico and Wilen (2001). Here, each fishing site has a different distance from the village, creating spatial heterogeneity. Similarly, sites neighboring the edges of the marinescape disperse with less neighbors than inner sites, creating heterogeneity in dispersal. Our model also differs from Sanchirico and Wilen's assumption of rent dissipation in each site because we explicitly model the site and effort choices of individuals.[1]

The villager's fishing labor is used as an input to harvest fish following a standard harvest function, identical for all villagers:

$$h_i = l_{fi} \cdot x_i \cdot q_i,$$

where the harvest in a given site (h_i) depends on the amount of labor time used (l_{fi}), the stock of fish in site i, (x_i), and the catchability coefficient in each site (q_i). The harvest does not depend directly on the number of other fishers in the site (*i.e.,* no congestion costs), but it depends indirectly on the other fishers' harvest in the site through the steady state equilibrium stock effect. The total harvest in a given site is the sum of all fishers' harvest in the site, and dynamic stock effects occur through the impact of harvest on the state variable x_i (an element of vector $\boldsymbol{X}$ in the equation of fish dynamics) in the steady state. Given this interaction of villagers' decisions in determining the steady state, a steady state spatial Nash equilibrium defines the fishing site choices for each villager, in which each villager has no incentive to move to another site nor to alter their optimally chosen labor allocation. To simplify the problem, we constrain the villager to fish in at most one site.

Finally, all villagers share the same goal of income maximization:

$$\max_{l_w, l_f, i} E[ph_i(1-\phi_i) + w(l_w)^{\gamma}\ ],$$

where p is the exogenous price of fish, w represents the onshore wage rate, and $\gamma \in (0,1)$ allows for diminishing returns to onshore wage labor to reflect imperfect labor markets.[2] The

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[1] In the cases presented in this paper, all the results lead to rent dissipation after covering the fixed costs of distance.
[2] Most fisheries models ignore the outside option of earning non-fishing income or rely on rent dissipation with
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respect to a constant opportunity cost. In reality, artisanal fishers in low-income countries typically mix fishing with onshore labor. Our framework allows for (realistic) variation on the intensive margin of fishing effort, and on villagers' ability to exit fishing in response to an MPA.

enforcement parameter ϕ_i enters the fisher's objective function to reflect the probability that the manager detects illegal harvest in site i. In keeping with the lower-income country setting, the model posits that fishers lose their illegal harvest when caught, while incurring time costs, but not incurring an additional fine. The parameter ϕ_i is equal to 0 if the site i is not a part of the protected area, and equal to $\phi \in [0,1]$ otherwise. The level of enforcement (ϕ) inside the protected area is chosen by the MPA manager and enters the fishers' objective function to reflect the probability that the fisher is caught while fishing illegally in a protected area, which reduces his expected income from that site and effort choice. Complete enforcement, $\phi = 1$, implies that no illegal harvesting goes undetected; no-enforcement, $\phi = 0$, implies that no illegal harvesting is detected; and incomplete enforcement, $\phi < 1$, might deter some or all illegal harvesting depending on the fishers' alternatives.

Manager

The role of the manager is to set up a Marine Protected Area to maximize one of four goals. First, we consider two economic goals: maximizing total yield (including legal and illegal harvest) and maximizing income (from fishing and non-fishing activities). Much of the fishery/MPA economics literature focuses on yield, which can be treated as isomorphic with income in the absence of a non-fishing outside option. However, income *inclusive of onshore wages* aligns more closely with the objective function of MPA managers in low income countries. Second, we consider two ecological goals: maximizing avoided fish stock losses inside the MPA (which mimics the park effectiveness literature in not considering leakage) and maximizing avoided fish stock losses across the marinescape (which incorporates leakage of effort that generate stock losses to non-MPA sites). Based on stakeholder interviews, income and marinescape fish stock goals reflect the two most common goals of managers but we include the other goals for comparison with the economics literature.

In this model, setting up an MPA boils down to three choices in the marinescape (*i.e.,* the $R \times C$ matrix): the site of the MPA (*i.e.,* specific cells in the matrix), the size of the MPA (*i.e.,* number of cells in the matrix), and the level of enforcement to exercise (ϕ) (here, the manager chooses one level of enforcement throughout the MPA). The manager is not naïve and accounts for the fishers' optimal response to the MPA, thus, the manager optimizes over the outcome of fishers' Nash equilibrium site and labor choices in response to the MPA at the steady state for fish stocks. In addition, appropriate to a low-income country setting, the manager often makes choices subject to a budget constraint. Following the optimal enforcement literature, managers incur enforcement costs, which here follow a linear and additive form (Nostbakken, 2008; Milliman, 1986; Sutinen and Andersen, 1985).

Solution method and parameters

The model is not analytically tractable, and we solve it using numerical methods for a specific spatial setting in Figure 1; we use a 2×3 grid (*i.e.,* 6 fishing sites) with one fish subpopulation located at the centroid of each cell of the grid. A single village located at the top of the leftmost column, nearest to the first site provides an asymmetric benchmark marinescape with six biologically identical fish sites that differ only in their distance from the village. The fishers' travel time is simply the Cartesian distance from the village to the centroid of the fishing site. Table 1 presents all parameters.

III. Results

A. Open-access (baseline)

A manager who wishes to use a Marine Protected Area (MPA) to maximize "avoided fish stock losses" needs a baseline to compare the stock outcomes with the MPA. In this paper, we use the open-access (*i.e.,* marinescape without a MPA) as the baseline. Thus, in evaluating the outcome of the policy, the manager cares about the change relative to the values in the open-access (*i.e.,* additionality) instead of the absolute values. In this analysis, we use the model of fishers' decisions to determine the resource extraction pattern in open-access working from the opposite starting point, but in similar fashion, to the empirical park effectiveness analysis' use of a von Thunen model and propensity score matching to predict patterns of resource extraction that would occur without Protected Areas.

The open-access equilibrium finds fishers and fishers' labor distributed across 5 of the 6 sites (Figure 2). In the first graph of Figure 2, we show labor allocation per fisher in each site. For example, in site 1, each fisher who fishes in site 1 spends about 11 hours fishing (white), about 1 hour traveling to the fishing site (light gray), and the remaining 12 hours working onshore (black). Note that this graph does not fully reflect the spatial configuration, instead, it shows the vectorized form of the $R \times C$ matrix (see Figure 1). For example, the time spent traveling to a site increases the farther from the village to the fishing site, thus, the traveling time increases monotonically in the first row of the matrix (sites 1, 2, and 3). However, travel time to site 4 is lower than to site 3 because site 3 is in the first row, but far from the village, and site 4 is in the second row, but in the same column as the village. In sites with no bar, such as site 6, no one fishes. In the second graph, we show total fishing labor per patch and the number of fishers in each site. This graph shows, for each site, the fishing time per fisher shown in the first graph multiplied by the number of fishers in the site. The bars represent the total fishing labor and the numbers on top of the bars represent the number of fishers. The third graph shows the fish stock in each site.

[FIGURE 2]

Here, without a MPA, villagers spread out across the marinescape, but more fishers locate close to the village than far from the village due to distance costs (second graph, Figure 2). Site 1, closest to the village, hosts the highest total fishing labor (second graph, Figure 2), which results in lower fish stocks close to the village (third graph, Figure 2). The stock levels in each site, shown in the third graph of Figure 2, are the baseline to compare the stock levels with a MPA, required to calculate avoided stock losses.

Distance costs alone keep fishers from the most distant site (site 6) despite high equilibrium fish stocks there (third graph, Figure 2), just as distance protects the interior of forests surrounded by encroaching or extracting villagers (Albers 2010; Robinson et al. 2011). Distance costs incurred traveling to a fishing site reduce the labor time available for wage work and fishing, and multiple fishers in a site reduce the returns to marginal fishing labor. Those fishing in the site closest to the village (site 1) have the lowest travel costs but, due to the number of fishers in that site, allocate the least time to fishing and the most time to wage labor of all fishers (first graph, Figure 2). Similarly, the heterogeneity in dispersal here leads to sites in column two (sites 2 and 5) supporting more fishing than sites in column three (sites 3 and 6), and only slightly less than sites in column one (sites 1 and 4), as reflected by the higher number of fishers and fishing in column two's nearshore site (site 2) than in column one's off-shore site (site 4), despite column two's site being slightly further from the village.[3]

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[3] In comparison to the current parameters, homogeneous distance costs lead to a smoother distribution of fishing effort across space, but, showing the impact of dispersal, more fishers locate in column two than the edge columns

Villagers make their optimal fishing and onshore work labor allocation choices by comparing the marginal benefits of labor fishing in a particular site to the marginal benefits of wage work beyond fixed time costs of traveling to fishing sites.[4] In addition and consistent with stakeholder interviews in Costa Rica and Tanzania, distance costs enter fisher decisions as the opportunity cost, defined by wage, of time spent traveling to fishing locations.[5] The current base case parameterization and pattern of fishing effort reflects observations in Costa Rica, where fishers agglomerate near shore and fish less per person than the smaller number of fishers located at more distant sites (Madrigal, et al., 2017).

B. Budget-unconstrained Optimal MPA location, size, and enforcement level

Considering the reaction of villagers to a MPA and the open-access, four stylized types of managers each optimally choose an enforcement level and a set of sites that comprise an MPA to achieve their goal. To characterize managers in low-income country setting, we posit one MPA manager whose goal is to maximize income, but we also consider the literature's more common manager whose goal is to maximize yield. To characterize managers with a fish stock conservation goal, we posit a manager who maximizes the avoided aggregate marinescape fish stock loss (avoided stock loss at the marinescape level or ASL_marinescape), and we consider the park effectiveness literature's goal, and that of some ecological managers, in defining a manager who maximizes avoided fish stock loss within the MPA (avoided stock loss within the

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in this setting. Similarly, the no dispersal case also leads to a smoother distribution of fishing effort across space than the current case with dispersal, but the impact of distance costs encourages more fishers near the village.

[4] High wages induce villagers to allocate more time to wage work and less time to fishing. On aggregate, wage levels correlate negatively with fishing labor, harvests, and fish stocks while correlating positively with wage labor and total income.

[5] Analysis of this framework with wage equal to zero, or no alternative to fishing labor, implies that all villagers put all of their time into fishing and make location choices of fishing sites based on maximizing their yield because yield is equivalent to income maximization without an outside option for labor time. Because distance costs are based on time and valued at the on-shore wage, the zero wage scenario also limits the spatial aspects of the decisions to addressing the labor time constraint -- lower amount of time available for fishing in more distant sites – relative to the returns based on dispersal and the number of other fishers in each site.

MPA or ASL_MPA). Fishers react to the MPA and its enforcement by changing effort levels and fishing sites, which results in changes to the aggregate levels of yield, income, stocks, and MPA stocks and in the per-site fish stock and the per villager labor allocation for villagers fishing in each site. The optimal MPA size, location, and enforcement level for each goal varies with different budget constraints on enforcement spending; in this section, we consider managers with unlimited budget to enforce the MPA.

The last column in Figure 3 shows the optimal MPA choices for the budget-unconstrained manager (we discuss the remaining columns in the next section), with the number of fishers in each site identified in each cell of the marinescape in the figure, and the number of villagers who choose not to fish indicated by that number in the village location on the figure. Here, the four types of managers choose MPAs of different size, configuration (*i.e.,* selected sites), and enforcement levels. Both ASL-focused goal managers include the entire marinescape in the MPA at a high enough enforcement level to deter all fishing. Avoided stock losses in the marinescape (ASL_marinescape) and in the MPA (ASL_MPA) rise monotonically with increased enforcement until complete deterrence occurs.

[FIGURE 3]

In contrast, both the yield and income-focused managers choose small MPAs and low levels of enforcement (last column, Figure 3). Both managers use the MPA location and enforcement to spread fishers out, which counters the open-access over-extraction stock effect problem to increase both yield and income. Income and yield increase with enforcement at low levels of enforcement where that enforcement solves the over-extraction problem, but the highest levels of income and yield occur at fairly low levels of enforcement that do not completely deter extraction.

To achieve the highest level of yield, the unconstrained yield-focused manager places the MPA in the two most congested fishing sites in terms of numbers of fishers and total fishing labor (sites 1 and 2). In response to the MPA, the number of fishers and amount of fishing labor in site 2 declines dramatically as two fishers choose to fish in more distant sites, which leads to a large increase in the stock and the avoided stock loss in that site of the MPA, as compared to the open access case (first and last column, second row, Figure 4). That increased stock in site 2 creates more dispersal to neighboring sites including the other MPA site (site 1). That added dispersal enables fishers to maintain nearly as much fishing labor in site 1 of the MPA than without the MPA, despite enforcement's impact on the marginal value of harvest labor time. In the yield-max MPA case, small levels of enforcement deter some extraction across the marinescape but the MPA's primary impact occurs through its location and configuration combining to generate dispersal to high-fishing labor sites. This MPA generates avoided stock losses within the MPA sites but decreases stock sizes – negative avoided stock losses – in most non-MPA sites through the leakage of fishing labor to other sites and through dispersal (last column, third graph, Figure 4).

[FIGURE 4]

To achieve the highest level of income, the unconstrained income-focused manager also places the MPA in the 2 most congested pre-MPA sites but includes a third MPA site (site 5). In addition, the income-maximizing manager uses a higher enforcement level than the yield-maximizer, although this manager also chooses an enforcement level that does not deter all fishing harvest within the MPA even without a budget constraint. That MPA configuration plus enforcement level induces 2 fishers to exit fishing and work in the village, which further reduces the over-extraction pressure on fishing stocks in open access and improves aggregate income (first and last column, second row, Figure 5). The income-maximizing MPA creates avoided stock loss within the MPA that is partially offset by increased stock loss in two fishing sites, including the most distant one (site 6), in which no fishing occurs without the MPA (last column, third graph, Figure 4). Despite similarities between yield and income as goals, the unconstrained optimal MPAs to achieve these goals differ: Maximizing income with the MPA employs a larger – although overlapping in sites – MPA with a higher enforcement level than necessary to maximize yield. In addition, the income-maximizing MPA deters more fishing effort, including inducing exit from fishing for wage-work.

[FIGURE 5]

While optimal enforcement for the ASL-based goals occurs at complete deterrence of fishing, in both the yield and income-focused cases, the optimal enforcement level does not preclude all fishing within the MPA; optimal enforcement levels do not imply complete deterrence of fishing for these goals. In addition to the differences across manager goal MPAs in optimal enforcement levels, the size and configuration of the MPA differs across goals with yield-maximizing MPAs as the smallest and all MPAs enforcing to reduce harvest in, or increase dispersal to, areas near the fisher's village port.

C. Budget-constrained optimal MPAs

In many settings and in this analysis, budget constraints limit the level of enforcement that a manager can exert within a MPA, which affects the decisions for the other choice variables of MPA location and MPA size. In this section, we discuss the optimal MPA choices of budget-constrained managers. In Figures 3, 4, 5, 6, and 7, we show the outcomes from optimal MPAs at different budgets.[6] In all the figures, the first column is almost identical to Figure 2 and

[6] Note that in these figures, the third graph shows the avoided stock loss, ASL, as opposed to the level of stock itself shown in the open access case in Figure 2.

represents the open-access in which the probability of losing the harvest (ϕ) is zero. Columns 2 through 6 represent managers with increasing budgets for enforcement, up to the budget-unconstrained manager described in the last section.

[FIGURES 6, 7]

Differences in MPAs Across Management Goals. For each management goal, the location and size of the MPA changes with increases in the enforcement budget until the budget permits the optimal amount of enforcement for the optimal MPA size and siting (Figure 3 and 8). Because optimal enforcement occurs at relatively low levels of enforcement for the yield and income maximizing goals, the optimal size and configuration of MPAs changes across only small budgets for these goals. For each budget level, the location and size of the constrained optimal MPA differs across management goals. Here, across budget levels, managers with either avoided fish stock loss goal typically select larger MPAs than managers with yield or income goals (Figure 3 and 8). Managers with yield and income goals typically locate their MPAs close to the village where the MPA restrictions solve some of the open-access over-extraction problem that arises from low distance costs in sites near the village. Despite these general patterns, the specific size and configuration of constrained optimal MPAs for each objective vary across budget levels and across management goals (Figure 3).

[FIGURE 8]

MPA Size Choices. For each management goal, the available budget for enforcement influences the optimal MPA design, as evidenced by the changes in optimal MPA sites and size across budget levels (Figure 3 and 8). Because the enforcement budget is constrained to spread evenly over all MPA units, the budget constraint on enforcement influences the constrained-optimal MPA size. At low budgets, a smaller MPA enables a high enough enforcement level to induce fisher behavior changes.

For the yield and income maximizing managers in general, as budget increases, the MPA size increases for each manager goal until the unconstrained optimal size is reached (Figure 8). Across budgets, the yield maximizing MPA is never larger than the income maximizing MPA and is typically smaller. At moderate budgets, the yield and income maximizing MPAs achieve their unconstrained optimal size.

The relationship between budget and size for the ASL managers reflects more tradeoffs between the enforcement level and the size of the MPA (Figure 8). Some increases in budget lead to increased enforcement levels but no changes in MPA size and configuration, which leads to increases in ASL. At many points, however, the increase in budget causes a discrete increase or decrease in the size of the MPA, and the related changes in enforcement levels as both the budget and the number of sites change. A marginal increase in budget can cause a decrease in the size of the MPA when that change permits a high enough enforcement level throughout the smaller MPA to produce more ASL. At high enough budgets, both ASL managers' MPAs include the entire marinescape (Figure 3). Overall, increases in the budget lead to increases in ASL but the optimal size of the MPA varies non-monotonically with budget because of tradeoffs between the size of the MPA and the level of enforcement possible within the MPA.

MPA Sites and Configuration Choices. In addition to differences across management goals in terms of enforcement level and MPA size, the particular sites or configuration of MPA sites also differs across management goals (Figure 3). The income-maximizing manager's MPA includes the near-village location at all budgets due to the negative impact of the congestion or stock effect in that location on income. In contrast, the yield-maximizing manager's MPA contains a completely different site at low budgets than the set of MPA sites at higher budgets, and never causes exit from fishing (Second column, Figure 3). At high enough budgets, the yield and income maximizing MPA sites coincide in the near-village locations but the income maximizing MPA also contains an additional site in the center column and a higher level of enforcement than the yield-maximizing MPA.

At low budgets, the ASL-marinescape maximizing MPA includes the high-fishing effort sites near the village where a small amount of enforcement induces declines in effort. In contrast to the income maximizing MPA, however, at larger budgets the ASL-marinescape MPA does not include the nearest-village site until the entire marinescape is included at very high budgets. Instead, increases in budget enable the ASL-marinescape MPA to include sites at a moderate distance from the village where the combination of the enforcement level and the distance costs leads to deterrence of fishing in the MPA. The ASL-MPA manager's MPAs tend to focus on sites where complete deterrence occurs until a high enough budget level to encourage exit.

Impact on behavior including exit from fishing. Although the choice variables for the MPA optimization decisions include the set of sites – which establishes both the MPA size and configuration – and the enforcement level, the reaction of fishers to the MPA determines the ecological and economic outcomes of the MPA. Because the optimal choices are based on that reaction, the choices of set and enforcement implicitly rely on how fishers respond to number of sites, location, and enforcement of the MPA. The location of MPA sites enters villagers' decisions through the impact of distance costs on fishing site choice. In addition, the location of MPA sites can alter dispersal, which affects returns to fishing in different sites. The level of enforcement in a MPA enters villagers' decisions by informing the expected returns from fishing within the MPA, with enforcement causing a range of responses including fishers marginally reducing fishing effort in an enforced site, fishers relocating their fishing effort to another site, or fishers exiting fishing to become wage-specializers. The total area of the MPA enters fisher decisions, in combination with enforcement, through higher enforced areas meaning larger stock effects and lower resource rents in non-MPA sites.

Managers with different goals use the combination of these choices differently. The ASL-MPA maximizing manager creates large MPAs at all budget levels that include the near village site, induce villager exit at high budgets, and marginally reduce fishing labor within all MPA sites rather than shrinking the MPA at low budgets (Figure 7). In contrast, the ASL-marinescape maximizing manager consistently aims to create higher stocks by establishing complete deterrence in many sites (no fishing) and by inducing exit from fishing, but the size and location of the MPA vary considerably across budget levels (Figure 6). Similarly, at high budgets, the income maximizing manager chooses MPA sites and sizes that lead to exit from fishing and to sites with complete deterrence, with two fishers exiting fishing and one site in the MPA with complete deterrence (Figure 3). Dispersal from that perfectly enforced site leads a fisher to choose the most distant fishing site (site 6) that distance protects without this dispersal (Figure 5). Both this manager and the yield-maximizing manager also use the location and enforcement to encourage fishers to spread out to reduce income-depressing over extraction near the village and do not completely deter harvest in the MPA. In contrast, however, the yield maximizer's optimal MPAs never induce exit from fishing (Figure 4).

IV. Policy Implications and Discussion.

This section considers the implications of the results described above for: understanding the losses associated with conservation policy that expects costless enforcement; explaining losses associated with the failure to incorporate the fishers' re-optimization during MPA site selection; differences between maximizing stock and maximizing ASL; implementation of MPAs that are not no-take reserves; marinescape versus MPA perspectives; and for future research.

Losses from neglecting enforcement costs in MPA siting decisions. Despite the reality of incomplete and costly enforcement, particularly in lower income country protected areas, economic models, implementation software, and managers tacitly assume that enforcement results in perfect compliance or that such enforcement is costless. That assumption leads to chosen MPAs generating fewer conservation benefits than intended due to unexpected illegal harvests in the MPA. In addition, failing to consider incomplete enforcement in optimal MPA siting and sizing decisions leads to inefficient MPA site and size choices. To demonstrate the impact of these suboptimal decisions, we first determine the optimal ASL-marinescape maximizing manager decision and the optimal ASL-MPA maximizing manager decisions when enforcement is assumed to completely deter harvest in the MPAs. We then use the model of fisher and fish reactions to those MPA configurations when the MPAs are enforced at the levels possible given a particular budget and calculate the actual outcomes from those incompletely enforced MPAs. In both ASL-marinescape and ASL-MPA maximizing manager cases, the optimal MPA with costless enforcement covers the entire marinescape. At a low budget, “5”, to cover true enforcement costs, this large MPA doesn’t alter fishers’ site decisions and only marginally decreases their fishing. The MPA with the budget constrained level of enforcement generates 30% and 18% of the avoided stock losses created by the optimal MPAs and enforcement at that budget, for the ASL-marinescape case and the ASL-MPA case, respectively. Because enforcement spreads across the entire MPA and this naïve manager’s MPA is large, the MPA at this budget has minimal impact on fisher’s decisions. Even at five times the budget, “25”, the naïve manager’s MPA generates 83 percent and 74 percent of the avoided stock loss created by the optimal MPA size and configurations, for ALS-marinescape and ALS-MPA managers, respectively.

To gain further insight about the inefficiency associated with a naïve manager’s implicit assumption that complete deterrence occurs in the MPA, we also examine the optimal location of a 1-patch MPA for the naïve, ALS-marinescape, and ALS-MPA managers. The naïve manager attempting to maximize ALS-marinescape or ALS-MPA places the MPA in the patch closest to the village (site 1) and expects to avoid all stock losses – perfect deterrence of fishing – in that site and induce 2 fishers to exit fishing, while recognizing that other fishers may relocate and offset those gains with higher harvests elsewhere. At a budget of “5”, the optimal ALS-marinescape and ALS-MPA managers place the MPA in site 2 and enforce at the level that budget permits. The naïve manager’s MPA generates 55% of the ASL that manager anticipates receiving and 93% of the optimal one-patch MPA’s ASL. The naïve manager focusing on ASL-MPA generates 36 percent of the anticipated amount of ASL-MPA and 56 percent of the value generated by the optimal MPA and enforcement at that budget level.

In both the unconstrained size and one-site MPA cases, naïve managers who anticipate that fishers will re-optimize following the MPA implementation but who assume that the MPA will completely deter fishing select MPAs that are suboptimal in terms of their size or specific sites. Because fishers react to the level of enforcement in the MPA and harvest illegally within the MPA, these naïve MPAs produce lower benefits than the manager expects. In addition, those benefits are lower than those achieved by fully incorporating the fishers’ re-optimization with respect to the enforcement level achievable at different budgets. In the systematic conservation planning academic literature, the impact of enforcement activities on extractor decisions rarely enters protected area siting decisions. In practice, no protected area siting software contains enforcement costs and the reaction of fishers to those costs within the siting and sizing decision. In addition, the economic literature on terrestrial park effectiveness also largely ignores the impact of enforcement spending on that effectiveness. Given the paper-park phenomena and statements from MPA managers that enforcement budgets are lower than needed to induce compliance, these results demonstrate that recognizing how fishers respond to incomplete enforcement produces more effective MPAs, in terms of both avoided stock loss within MPAs and across the marinescape. Here, the interaction between optimal size and configuration of MPAs and constraints on the ability to enforce the MPA drives differences between the naïve manager's expected outcomes and both the actual and optimal outcomes. These findings demonstrate the lost conservation opportunities that standard MPA siting frameworks incur due to their failure to consider costly enforcement and fisher's reactions to incomplete enforcement following MPA establishment. Ignoring enforcement costs and fisher reactions to enforcement limits the conservation gains possible from MPAs. Economic efficiency requires decisions based on the reality of costly and incomplete enforcement – whether due to budget constraints or optimal marginal tradeoffs.

Losses from ignoring fisher re-optimization in siting MPAs. Discussions with organizations and managers that make MPA siting decisions portray various implicit assumptions about how fishers will react to an MPA that differ from the economic assumptions here of fisher re-optimization in fishing effort and fishing location or site decisions in response to an MPA. For example, in addition to an implicit assumption that complete deterrence from fishing in the MPA occurs, some frameworks assume that fishers that formerly fished in the MPA will exit fishing and other fishers will not re-optimize their effort and location decisions.

A manager using that combination of exit and no re-optimization assumptions in defining MPAs expects higher levels of ASL-marinescape than occur when fishers can re-optimize across fishing effort and location decisions. Even within the setting of complete enforcement, ignoring how fishers re-optimize in terms of fishing versus wage labor and in fishing locations following the MPA leads to inappropriate choices for the size and configuration of the MPA and lower conservation benefits that MPAs based on fishers' re-optimization in response to the MPA.

Maximizing MPA Stock versus Maximizing MPA Avoided Stock Loss. Some frameworks for selecting the sites to include in protected areas focus on conserving the highest possible stocks rather than using Protected Areas (PA) to produce the highest avoided stock losses; the emphasis is on stocks rather than on the additionality of the policy. Although maximizing ASL-marinescape and maximizing marinescape stock are identical, managers that seek to maximize the stock in the MPAs create different MPA networks than managers that maximize ASL-MPA. At high enough budgets, both the stock-MPA and ASL-MPA managers put the entire marinescape into the MPA. At lower budgets, the stock-MPA manager consistently uses large MPAs to "get credit" for many site's stocks. At those lower budgets, the ASL-MPA manager uses smaller MPAs which permits higher levels of enforcement and more effectiveness at generating conservation; and typically emphasizes either MPA units with zero fishing or MPA configurations that encourage fishers to exit fishing. These results demonstrate the missed conservation opportunities that derive from decision based on total stock size rather than on the conservation additionality created by the MPA.

Beyond No-take Zones: IUCN Classifications. Limited enforcement budgets in lower income country Protected Areas (PA) lead to illegal harvest, or poaching, within PAs, with the results here determining optimal MPAs that consider poaching's harvests. In addition, the results here find that some budget levels and some manager goals lead to MPAs with optimal illegal harvest. In practice, locations with enforcement and illegal harvest often witness costly conflict between PA guards and villagers that managers may seek to avoid (Robinson et al., 2010; Walpole, 2003; Nepal and Weber, 1995; Leader-Williams and Albon, 1988). To avoid these costs, but still achieve their objectives, managers in low-income country settings could choose a less restrictive IUCN classification of their MPA rather than implementing incompletely enforced no-take reserves. For example, some of Tanzania's MPAs permit fishers to harvest within MPAs, with managers enforcing gear restrictions or community access restrictions instead of permitting no harvest. However, these MPAs still require management and enforcement. Some empirical terrestrial research suggests that extraction-permitting PAs can avoid more deforestation than more restrictive PAs (Pfaff, et al. 2014; Ferraro, et al. 2013). Future research to understand the actions of extractors in such non-no-take reserve settings and the costs of enforcing these extraction rules could form a foundation for PA manager optimal choices over the MPA size, location, enforcement, and permissible access restrictions through the IUCN classification to achieve both ecological and economic goals.

MPA- v. Marinescape-Focused Resource Conservation. Based on discussions with MPA managers about their goals in establishing MPAs, this analysis posits two types of managers that base policy on avoided fish stock losses, with one taking a full marinescape perspective and one focused only on the avoided losses within the MPA. The ASL-MPA-focused manager's decisions do not consider the impact of leakage of fishing effort to non-MPA sites, which presents clear inefficiencies for management from a land- or marinescape perspective. Although inefficient, many organizations and managers base their assessment of success on in-MPA status and economists evaluating park effectiveness consider the avoided losses within the park rather than across a landscape. In contrast, in other settings, such as establishing REDD forests, landscape perspectives and the role of leakage prove central to the discussion, albeit often without a model of how resource extractors respond to a policy to create leakage. In accordance with their different goals, at many budget levels, these two managers create MPAs with different sizes, configurations, and enforcement levels (Figure 3). With a focus on reducing fishing effort within the MPA, the ASL-MPA manager locates the MPA where it generates large avoided stock losses without considering any offsetting stock losses elsewhere. For example, at a budget of "35", the ASL-marinescape manager uses a large MPA that generates only one location of leakage and negative avoided stock losses (Column 5, Figure 6) while the ASL-MPA manager uses a smaller and more enforced MPA that generates 3 locations of leakage (Column 5, Figure 7) that partially offset the marinescape gains from the MPA. These differences in MPAs between these two types of managers signals that organizations seeking efficient production of avoided stock losses across the marinescape must charge the MPA implementation team with that marinescape goal rather than assume that a high in-MPA effectiveness at avoiding stock losses correlates well with avoided losses at the marinescape level. In order to make such marinescape decisions, however, managers must predict the pattern of extraction that results from fishers re-optimizing after the MPA in their decisions, as done here. Economists can assist in MPA siting decisions by defining models of spatial reaction to potential MPAs to predict both in-MPA and marinescape avoided stock losses for a particular setting to improve the effectiveness of the MPA.

Ongoing and Future Research. This framework forms a foundation to explore other aspects of the socioeconomic and ecological settings of MPAs in low-income countries. In addition to detailed case study analysis, ongoing research explores socioeconomic aspects of these settings such as making on-shore wages endogenous to the labor supply and to MPA quality, incomplete labor and resource markets, and the role of alternative income generating projects or conditional and non-conditional payments in inducing conservation. Similarly, analyses of different ecological settings in terms of dispersal patterns, of heterogeneity across marine sites including hotspots, and of ecological goals other than resource stocks will provide further information for managers of these complex systems. Further work on heterogeneous enforcement patterns and contrasting enforcement through "caught in the act" and "caught with contraband" will also improve the efficiency of MPA management. In addition, analysis of the optimal MPA decisions during a dynamic transition from degraded resources to a steady state resource will prove particularly important for the lower income country context in which complete moratoria on fishing presents a problematic policy tool in the presence of subsistence fishers and excess labor.

V. Conclusion

The model results here inform the siting and management of MPAs in settings where fishers face labor allocation decisions and distance costs, and where managers face enforcement costs, limited budgets, and a range of MPA goals. Managers achieve avoided stock loss goals with large MPAs at a distance from a population center, and with enforcement that generates exit from fishing and complete deterrence where possible. Managers achieve income and yield goals with smaller MPAs located near ports, with enforcement levels that induce fishers to spread out to avoid over-extraction. The yield and income-maximizing MPAs often contain optimal – but illegal – fishing, and binding budget constraints can generate constrained optimal illegal fishing in the avoided stock loss MPAs. Still, yield and income-maximizing MPAs differ from each other in size and configuration, which implies that simplified models that do not distinguish between these goals miss important opportunities to improve incomes. Also addressing livelihood issues in low-income countries, the policy and academic focus on MPAs as no-take zones overlooks opportunities for less restrictive MPAs to improve ecological and economic outcomes, especially in settings with optimal harvests within MPAs described here. Optimal MPA locations take advantage of the relationship between distance costs and necessary enforcement levels but also use dispersal patterns created by MPAs in central locations to offset distance costs and stock effects. Marinescape outcomes respond to changes in enforcement levels in complicated, non-monotonic ways based on how fishers' re-optimize over fishing labor and fishing locations following introduction of an MPA, which interact with distance costs, dispersal, onshore wage, and enforcement probabilities.

For informing MPA policy decisions including size, location, and configuration, these results demonstrate that the response of villagers determines the optimal choice of the MPA, yet few models and fewer practical MPA siting and implementation procedures consider those reactions at the point of selecting MPA sites. With many countries dramatically expanding their MPA while also addressing poverty, managers that recognize the characteristics of artisanal fishers' decisions can avoid MPA policies that lead to unintended outcomes and inefficient MPA choices. MPA choices that assume near-perfect enforcement create inefficiently sized, inappropriately sited, and under-enforced MPAs that produce lower conservation outcomes than those that reflect enforcement costs and the fisher reaction to enforcement levels. Overall, MPA siting and management decisions that do not reflect the re-optimized equilibrium fisher response to the MPA overestimate conservation benefits and establish inefficient MPAs due to the misrepresentation of the fishers' reaction to the MPA and its enforcement in terms of illegal fishing, fishing site choices, and fishery exit.

NOTE TO BIOECON CONFERENCE REVIEWERS:

We have many other results that are not written yet. The presentation will incorporate more specific numbers describing the costs/losses of common assumptions in siting MPAs; other optimization cases exploring different levels of wage, distance cost homogeneity, and village location; and sensitivity analysis of all model parameters for the open access case.

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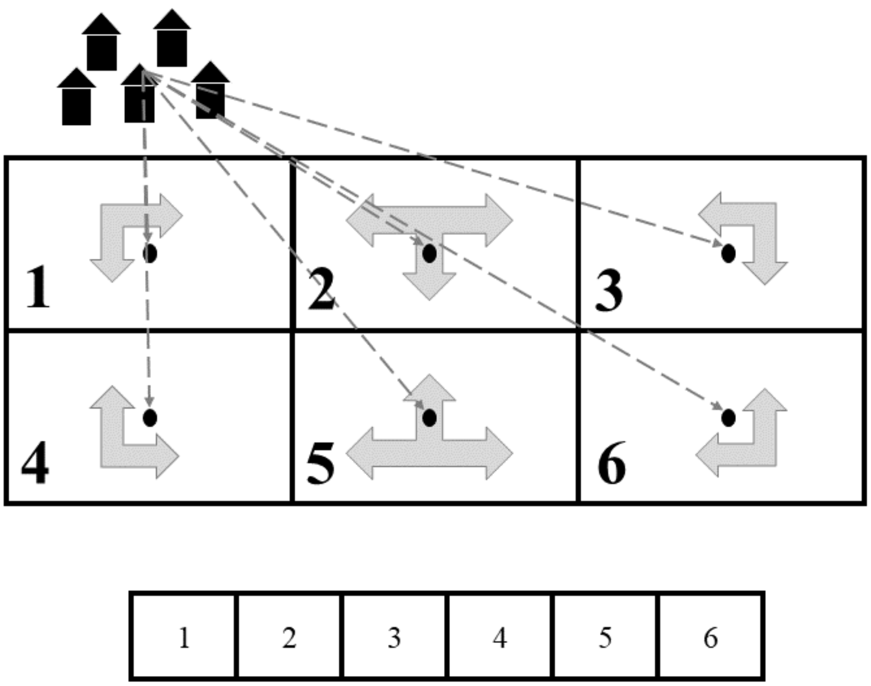
Figure 1. Spatial setting.



The dashed lines represent the distance from the village to each fishing site and the wide arrows show the dispersal of the fish within the marinescape.

Figure 2. Open access

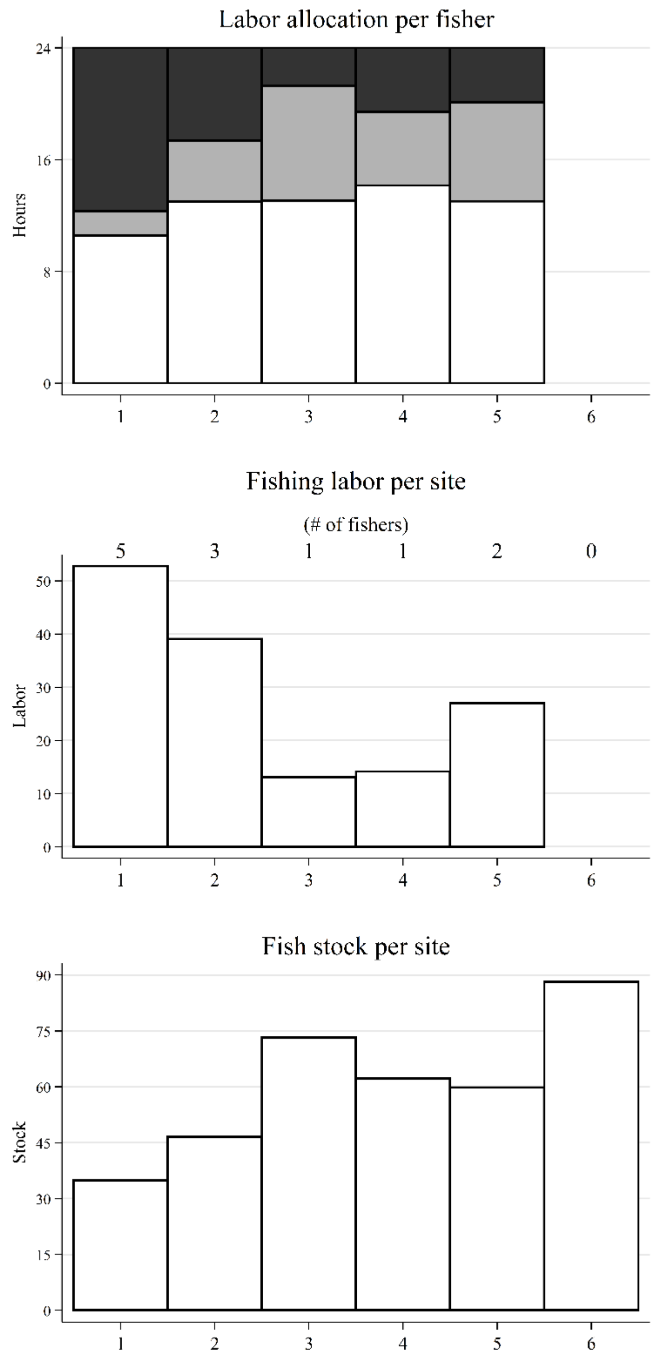


Figure 3. Optimal MPA for each goal

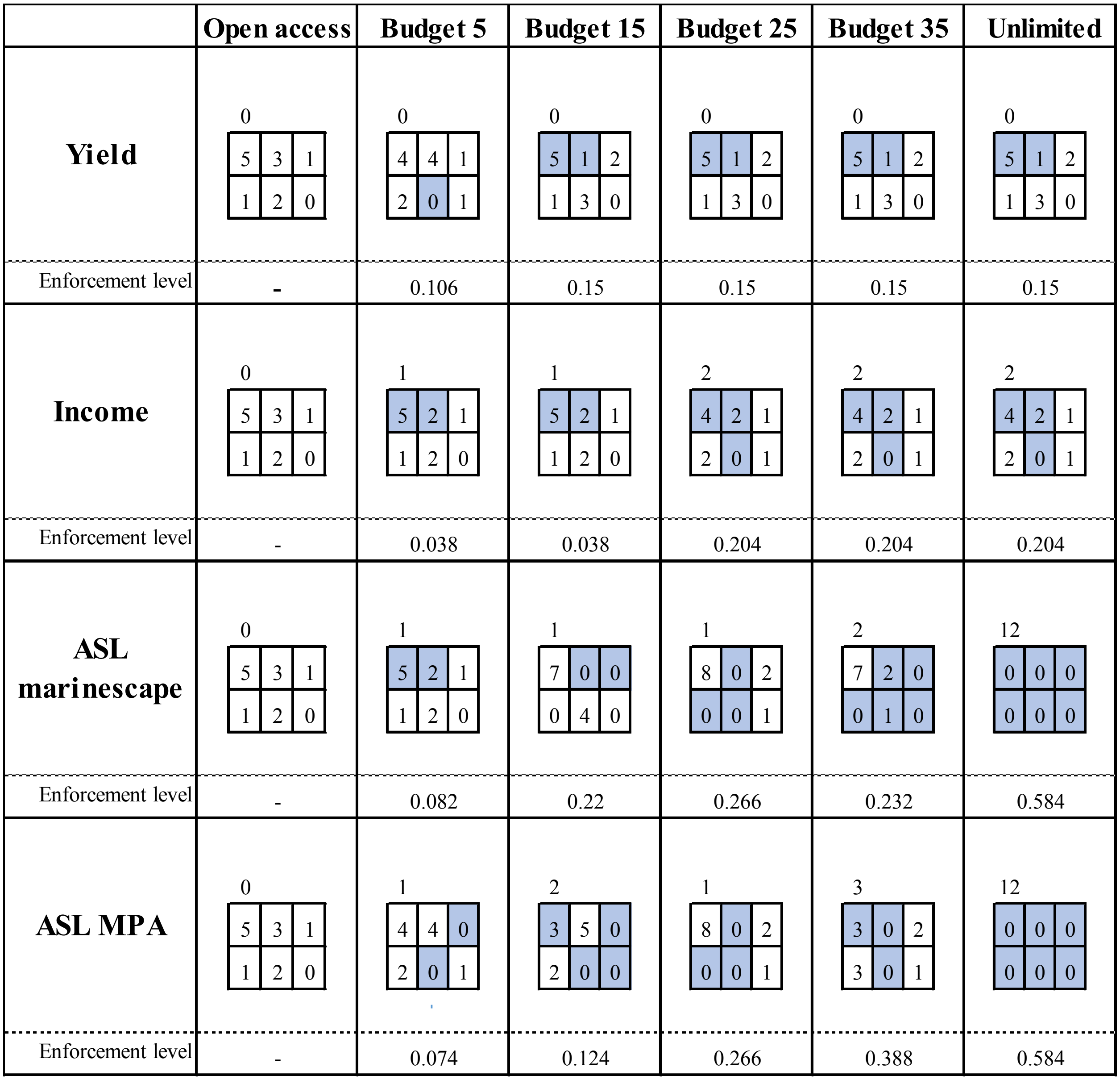


Figure 4. Optimal MPA to maximize yield

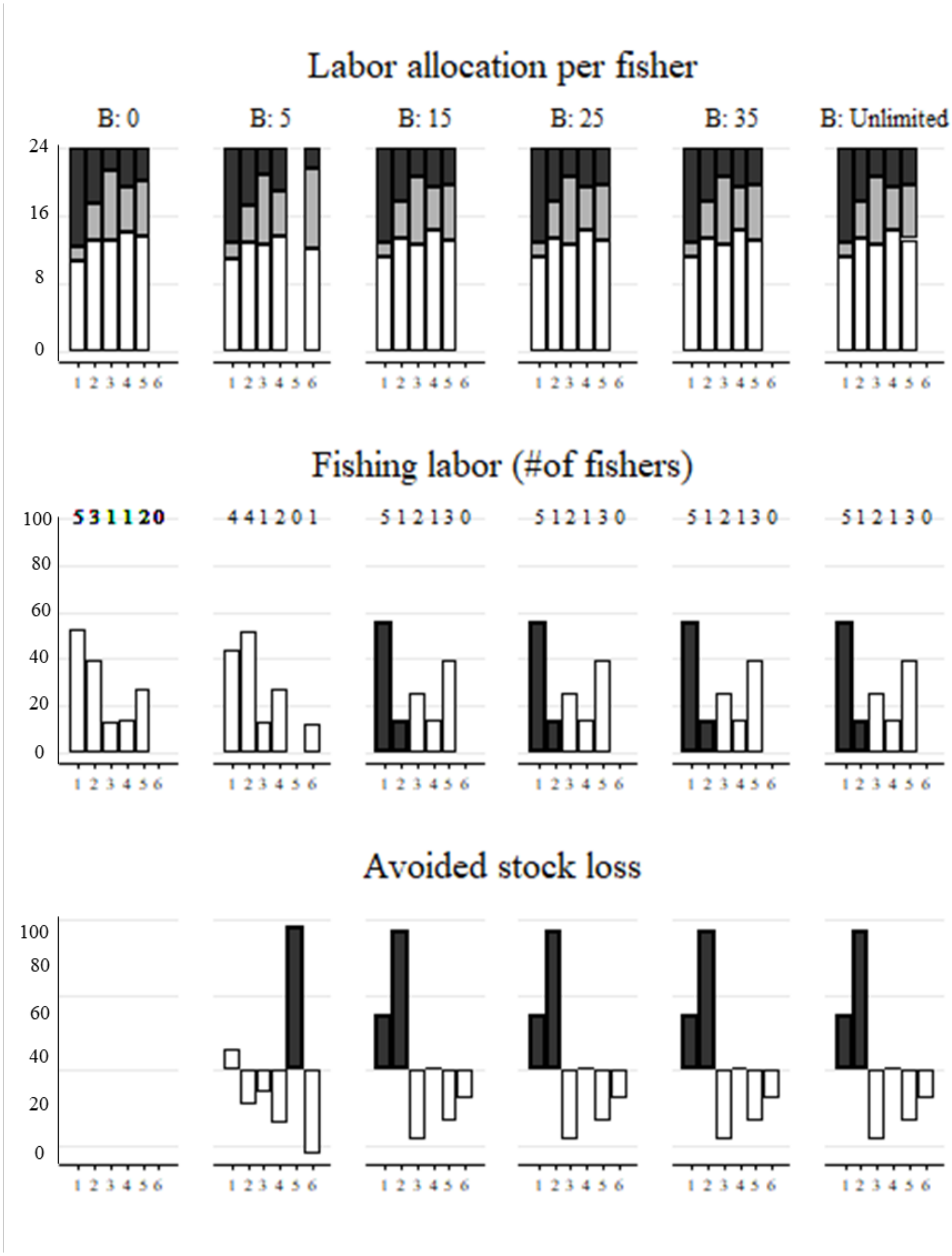


Figure 5. Optimal MPA to maximize Income

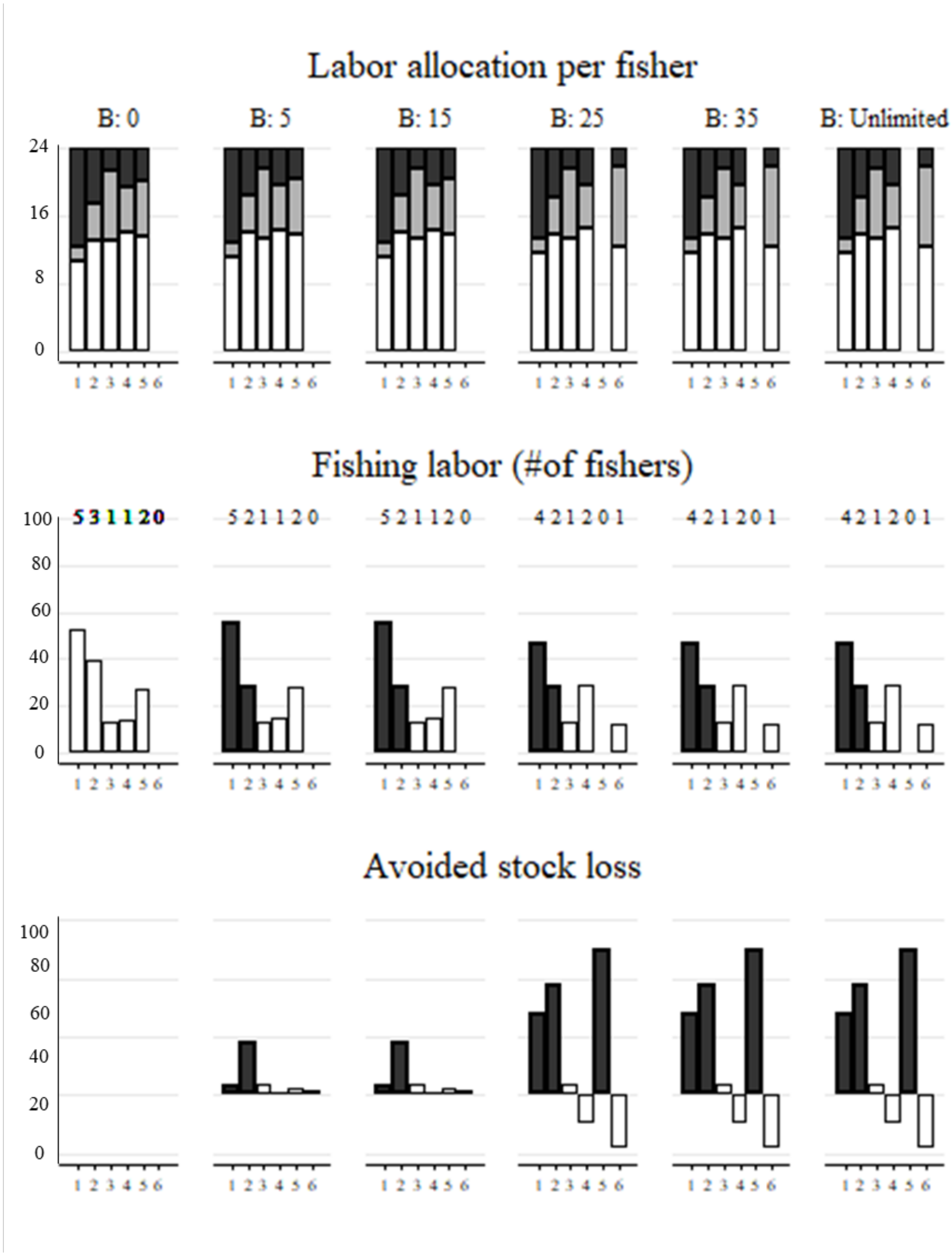


Figure 6. Optimal MPA to maximize ASL-marinescape

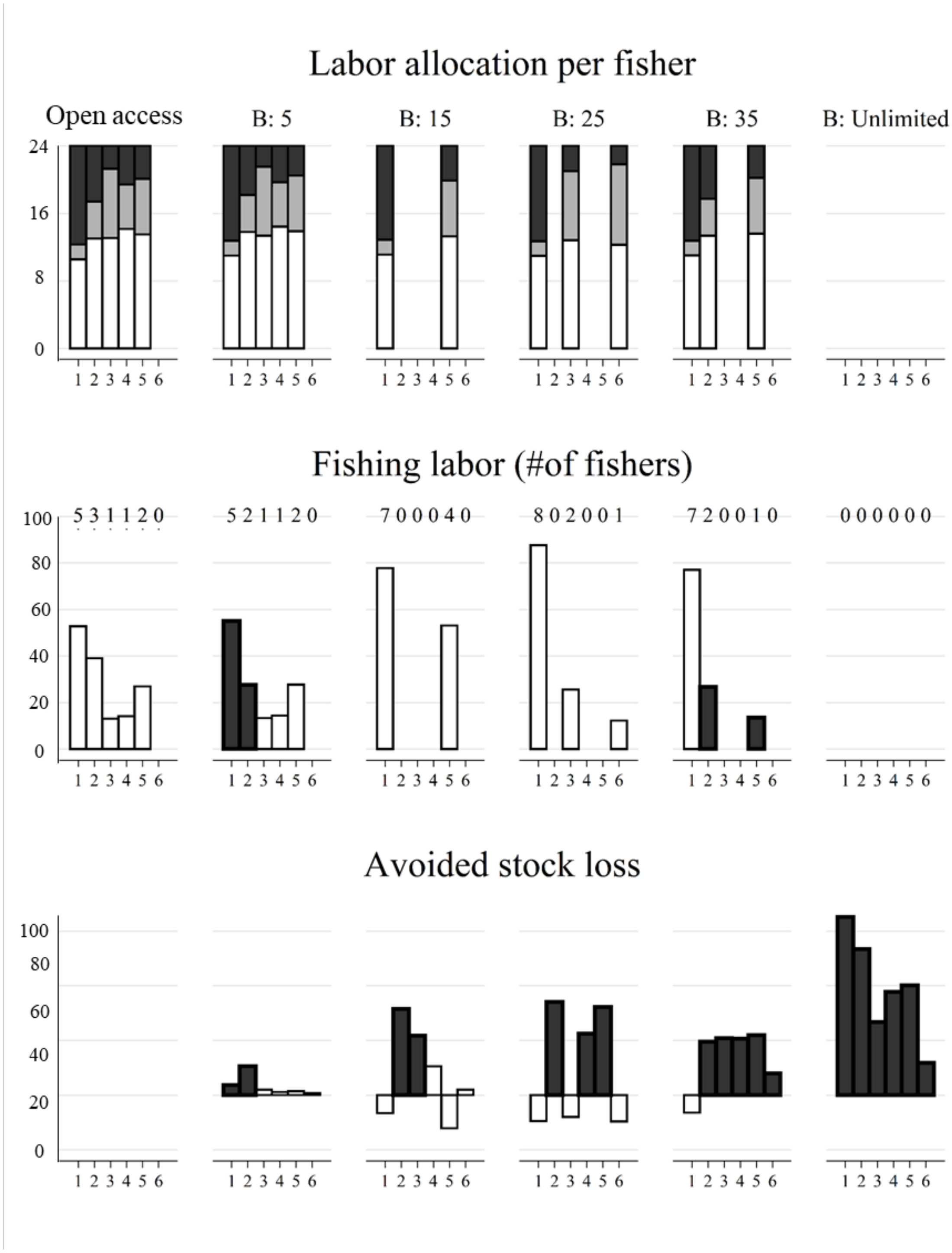


Figure 7. Optimal MPA to maximize ASL-MPA

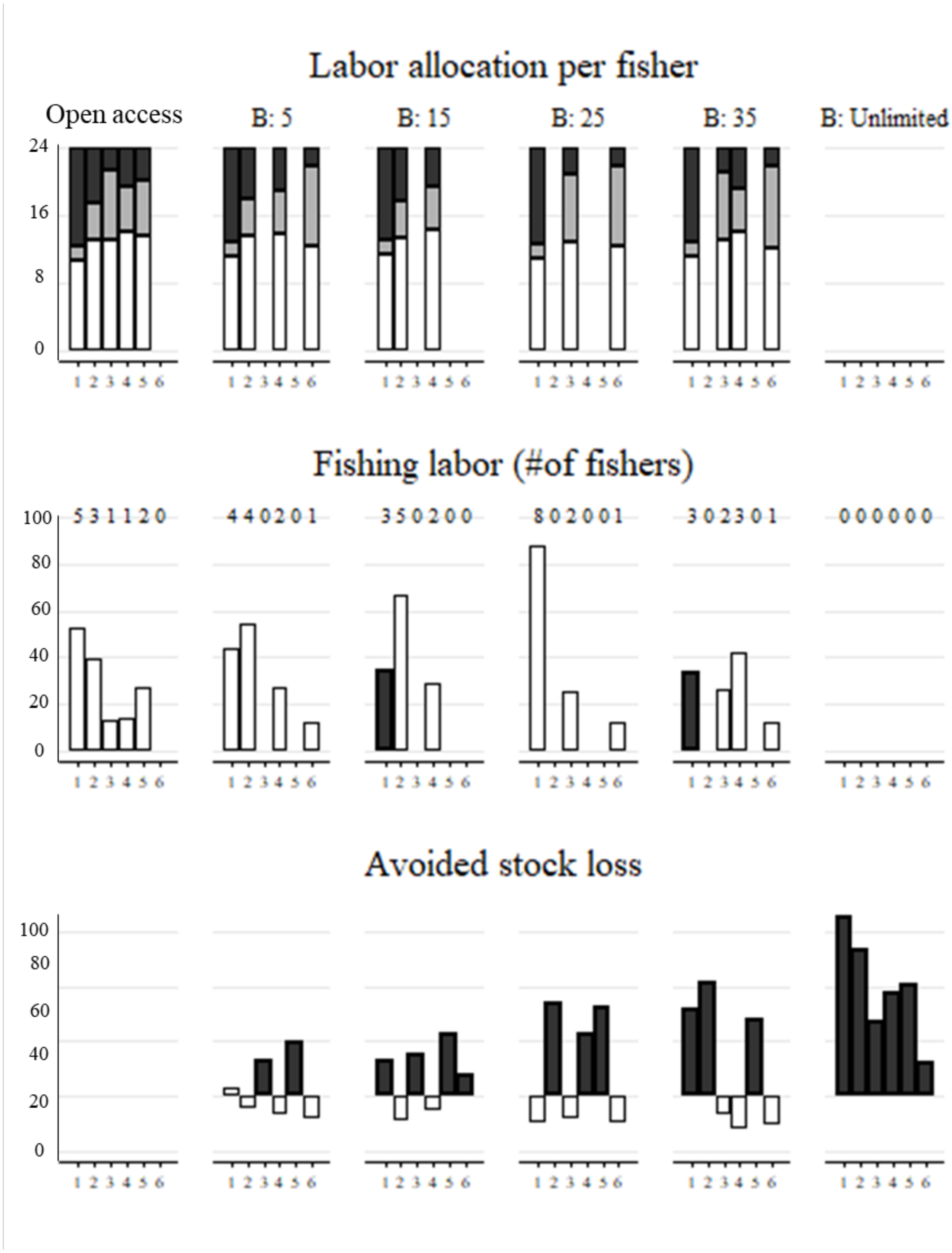
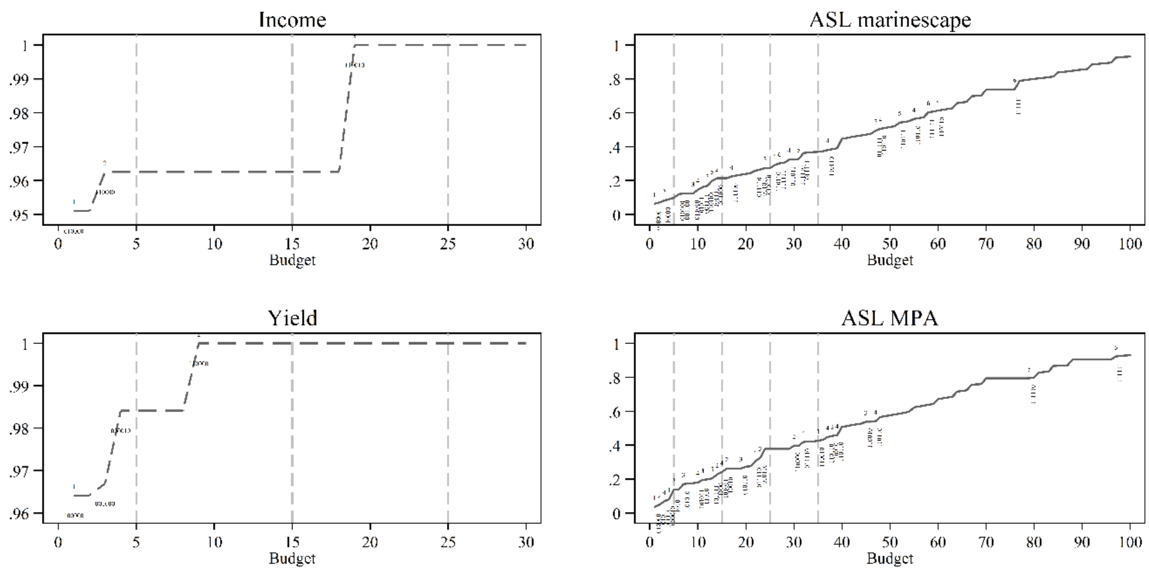


Figure 8. Relationship between budget to enforce and the size and siting of the MPA



All outcomes are expressed in normalized values in which 1 represents the best feasible outcome and 0 the worst feasible outcome. The number on top of the line represents a change in the size of the optimal MPA and the string below a change in the configuration. For example, 100000 represents a MPA that protects only site 1; 111000 represents a MPA that protects all sites in the first row (sites 1, 2, and 3); and 111111 represents a MPA that protects all the marinescape.

Figure 9. Relationship between optimal MPA and enforcement level

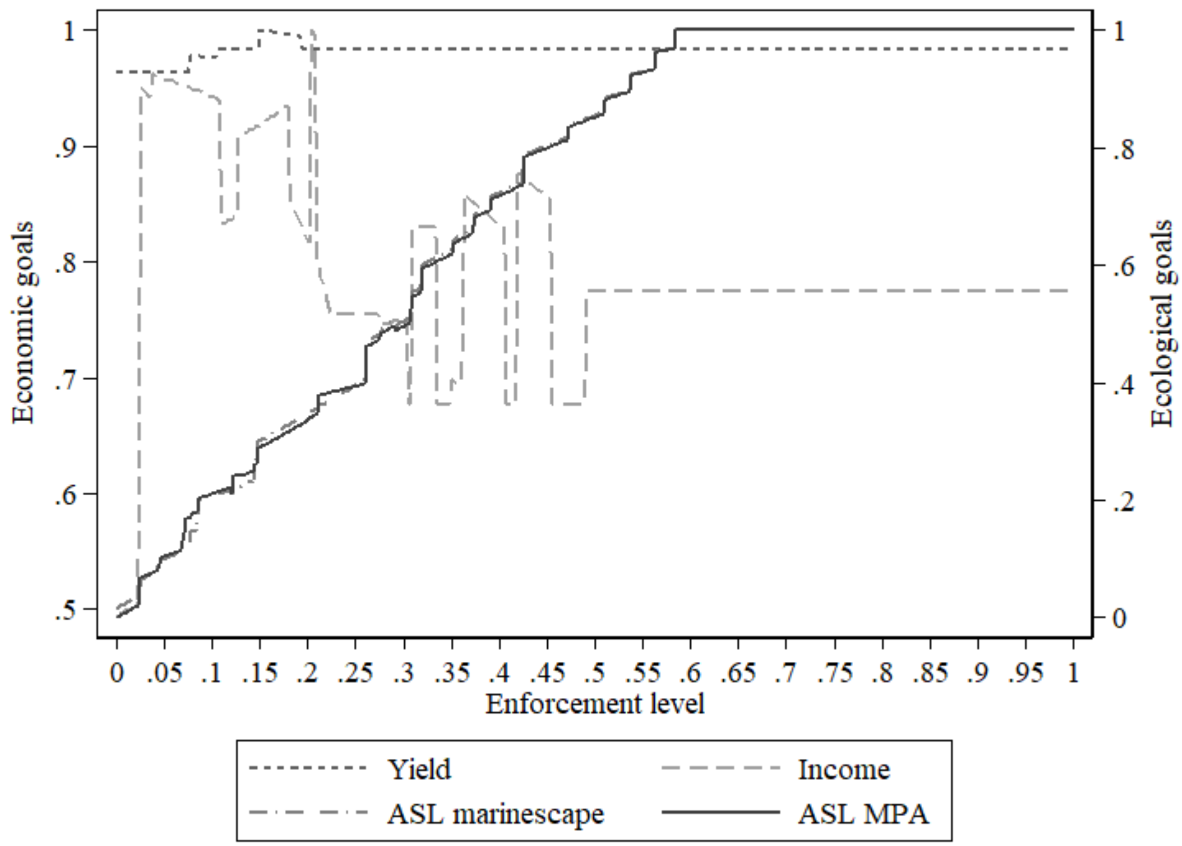


Table 1: Parameter Values

Description	Parameter	Value
No. of columns (moving along the coast)	–	3
No. of rows (moving out to sea)	–	2
Width of each column	–	4
Width of each row	–	3.5
Position of village by column	–	1
Number of villagers	N	12
Intrinsic growth rate	g	0.4
Dispersal coefficient (from Smith et al. 2009)	m	0.4
Price of fish	p	1
Wage rate for non-fishing labor	w	1.25
Wage parameter (opportunity cost of time)	γ	0.6
Total time available per person	L	24
Catchability coefficient	$q_j, \forall j$	0.007
Carrying capacity for each site	$K_j, \forall j$	100
Cost of $\phi_j = 1$ for one site	c	30