Optimal Siting, Sizing, and Enforcement of Marine Protected Areas in Lower Income Countries

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Abstract

In cases of incomplete enforcement, the reaction of potential resource extractors determines both the conservation and economic outcomes from protected areas (PAs), which implies that defining the optimal PA requires incorporating that reaction's impact in decisions. Using a spatially-explicit bio-economic model, this paper demonstrates how the optimal size, enforcement, and location for a marine protected area (MPA) in a lower-income country depend on characteristics central to such countries: low management budgets; low-valued alternative opportunities for fishers; distance costs to fishing sites; and livelihood and ecological goals. A manager chooses an MPA to maximize the yield, income, or fish stock that results after fishers react to the potentially incompletely enforced MPA. The spatial Nash equilibrium of fisher locations and effort at a steady state fish stock incorporates labor allocation decisions across income-generating activities, fishing location decisions as a function of distance costs, other fishers' behavior, and any MPA restrictions. Reflecting settings in Costa Rica and Tanzania, this analysis shows that optimal MPAs differ markedly across goals and budget levels; that managers make tradeoffs between the size, location, and enforcement level in choosing optimal MPAs; that illegal harvest in MPAs can be optimal, especially when small levels of enforcement solve some of the open access over-extraction problem; that fish dispersal and fishers' location decisions interact with MPA policies to have marinescape-wide implications including leakage; and that MPAs that generate exit from fishing rather than marginal declines or re-locating fishing produce high conservation benefits.

Key words: Marine protected areas; spatial; Nash equilibrium; bio-economic model; fisheries; development; no-take zones; marine reserves; enforcement; leakage; systematic conservation planning;

I. Introduction

Continuing the rapid increase in area of terrestrial and marine systems included in protected area (PA) or reserve networks, the Aichi Biodiversity Targets aim to protect at least 10% of coastal and marine areas within marine protected areas (MPAs) by 2020 (Pereira et al., 2013). Although much of this PA expansion will occur in lower income countries, the PA academic literature and policy implementation tools rarely account for the socio-economic and institutional characteristics of these settings. In any setting, the ecological and economic outcomes from PA siting and management are a function of how people, as potential PA resource users, respond to the PA. 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. In lower income countries where PA managers face limited budgets and institutions for enforcement, and where rural people depend on natural resources for livelihoods, PAs will create lower than expected ecological and economic benefits if PA management decisions fail to reflect people’s reaction to the PA.

This paper uses a standard spatial metapopulation framework with density dispersal of fish across multiple sites as the basis for considering how people’s reactions inform the optimal size, location, and enforcement level of an MPA. Reflecting the low income country setting, MPA managers facing costly enforcement aim to achieve one of several goals for the MPA within a marinescape – maximize yield, maximize income, maximize aggregate fish stock, and maximize MPA fish stock – subject to budget constraints and the reaction of villagers. In a model of fisher behavior based on observations in artisanal fisheries in Tanzania and Costa Rica, villagers make labor allocation decisions across fishing and onshore activities, face heterogeneity in distance costs to fishing locations, view enforcement of MPA restrictions as a disincentive to illegal harvest, and consider other fishers' decisions in determining their labor and fishing site location decisions, in addition to the standard fish dispersal. The spatial game theoretic model incorporates responses of individual fishers to an MPA policy and to the fishing and on-shore labor decisions of all other villagers. Fishers' best-response functions depend on both the spatial configuration of the MPA and the regulator's degree 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 central results demonstrate the interactions of dispersal and distance costs in optimal MPAs; reveal qualitative and quantitative differences in optimal MPAs established to achieve different goals; identify few opportunities for optimal MPAs to produce win-win situations in terms of ecological and socioeconomic outcomes; show changes in MPA configurations across budget levels; elucidate the complicated relationships between enforcement probabilities and MPA outcomes; and inform a policy discussion. The next section briefly discusses the academic and policy literatures on which this analysis builds. The following section presents the model of the marinescape, PA manager decisions, and fisher decisions, and the model's solution method. The fourth section describes the results of the manager optimization for MPA size-constrained and unconstrained cases across management goals and budgets. That section also examines the responsiveness of various outcomes to parametric increases in enforcement's probability of detecting illegal activities. The fifth section holds results from two parameter experiments to further explore the interactions of distance costs and dispersal in determining the optimal MPA and contains results from two policy experiments based on stylized versions of the Costa Rica and Tanzania settings. The penultimate section discusses policy implications of these results and the final section concludes.

II. Background and related literature

This paper builds from, and adds to, several strands of academic and policy literatures including spatial fishery economics, poverty-park interactions, systematic conservation planning, leakage, park effectiveness and avoided deforestation, labor allocation analysis in developing country settings, and incomplete enforcement.

The fishery economics literature evaluates MPAs using spatial metapopulation models to explore the impact of a no-take reserve MPA on fishing outside the MPA, typically finding that dispersal from a perfectly protected MPA rarely offsets the lost fishing in the MPA (Carter 2003; Smith and Wilen, 2003; Sanchirico and Wilen 2001; Hannesson 1998). These models typically focus on fish dispersal with less emphasis on the drivers of spatial fishing decisions or reactions to enforcement of MPAs. Yet, in addition to protecting biodiversity and ecosystem services, most MPAs explicitly recognize the role of the fish resource in livelihoods (Carter, 2003). Despite the prominence of livelihood issues in lower income countries and the rapid increase in planned MPAs in such countries, the economics literature rarely focuses on how the characteristics of these settings influence the effectiveness of MPAs (exceptions include Robinson et al., 2014; Gjertsen, 2005; and without an economic framework, Levine, 2006).

Extensive surveys and stakeholder interviews in Tanzania and Costa Rica identified central aspects of fisher decisions, MPA manager perspectives, and the institutional setting that the framework developed here incorporates (Madrigal, et al. 2015; Robinson et al. 2014; Albers and Madrigal, 2015). First, the model incorporates villager labor allocation decisions across fishing and wage labor, heterogeneity in distance costs to fishing locations, fishers' interactions in labor and location decisions, and incomplete enforcement of MPA restrictions. Second, managers report being faced with serious budget constraints for patrols and describe a range of relevant objective functions for MPA management, sometimes including both conservation and economic benefits (Albers et al., 2015; Silva, 2006; Gjertsen 2005). In particular, Tanzania's legislation requires MPAs to address both biodiversity and poverty alleviation, which led to managers developing poverty alleviation projects, gate receipt-based payment plans, and access rights for local people, in addition to enforcement activities (United Republic of Tanzania, 2011; 1994; Robinson, et al. 2014). In contrast, Costa Rica's Caribbean coast MPA management focuses on protecting fish stocks and sea turtles through no-take reserves, but high tourist visitation rates to PAs like Tortuguero National Park create onshore wage opportunities in the tourism industry.

The systematic conservation planning (SCP) literature defines steps to selecting and implementing a protected area or reserve system that emphasizes a landscape perspective and incorporates local people (Margules and Pressey, 2000; Pressey and Bottrill, 2009). In SCP frameworks, consideration of local people's interactions with the resources in a proposed reserve occurs throughout the process, including pre-establishment information meetings and post-establishment benefits-sharing mechanisms.

Although such participatory processes may encourage compliance with PA regulations, the potential reaction of people to the PA does not enter SCP at the step of choosing the best PA size, location, and management and, instead, often occurs through altering the optimally selected PA in *ad hoc* fashion, which undermines the efficiency of the PA in producing conservation benefits (Pressey and Bottrill, 2009; Albers et al., 2016). The empirical terrestrial park effectiveness and avoided deforestation literature finds that people continue to pose threats to resources within parks, although parks do discourage that resource use, but offers little information about how PA siting and management decisions alter people's PA resource use and the PA outcomes (Ferraro et al. 2013; 2011; Andam et al. 2008). Tying people's responses to PAs to a landscape perspective, economists assess the role of "leakage" in which people react to a PA, such as a REDD (reducing emissions from deforestation and forest degradation) forest, by relocating their extraction to another forest where that activity partially offsets the conservation gains generated by the PA (Delacote and Angelsen, 2015; Angelsen et al., 2012; Atmadja et al., 2012). Similarly, Robinson et al. (2011) determine the optimal PA size when villagers respond to PAs by relocating their extraction to a buffer zone in a setting with managers that consider the conservation benefits from the PA only or from the whole landscape, and when managers consider rural welfare in their PA decisions. In addition, enforcement and illegal extraction can create conflict between park managers and local people, which imposes non-economic costs that the "park effectiveness" and NTFP extraction literatures rarely address (Robinson et al., 2011; Sims, 2010; Andam et al., 2008). Still, both the academic and practical SCP literature do not incorporate the potential for people to disturb a PA's production of ecosystem services in making choices of PA location, size, and management.

This failure to consider people's ongoing threat to resources within PAs reflects an implicit assumption either that demarcating a PA ensures its protection or that enforcement of PA access restrictions completely deters illegal activity. In lower income countries, however, low management budgets imply limited ability to fully enforce a no-take PA and that PA managers face tradeoffs between fully protecting a smaller area or less effectively protecting a larger area. Despite evidence of commonplace illegal fishing and its role in informing marine reserve siting (Kritzer, 2004), early work on incomplete enforcement in fisheries (Milliman, 1986; Sutinen and Andersen, 1985), and limited PA management budgets in lower income countries (Bruner et al., 2004; Muller and Albers, 2004; de Oliveira, 2002), few economic analyses of MPAs incorporate incomplete enforcement. Byers and Noonburg (2007) examine a game theoretic model with illegal harvests in a marine reserve and costly enforcement to determine poaching's impact of the reserve outcomes, and to identify enforcement levels that induce compliance. That model's assumption of constant fishing effort ignores changes in fishing labor allocations, which interviews in lower-income countries suggest is critical to understanding the outcome of marine reserves (Albers, et al., 2015; Madrigal, et al., 2015). Yamazaki, et al. (2014) develop a bioeconomic model with illegal fishing that identifies the level of illegal harvest in the reserve and the neighboring regulated fishery, with particular insights about enforcement within and outside the reserve, the displacement or leakage of fishing with increasing reserve size, and the possibility of lose-lose situations with more poaching and lower total fish biomass with incomplete enforcement. Both of these articles present a two-region model – in or out of the MPA – in an implicitly spatial setting, but without modeling distance as a component of the fishing location choice. Davis et al. (2014) emphasizes TURF (territorial user right fishery) enforcement costs as a function of distance in an optimization that includes some no-take MPA zones, but without fish dispersal and fisher distance costs as part of zoning decisions. In contrast, this paper extends this limited literature on enforcement and poaching in MPAs by including a richer marinescape and a fuller model of fisher decisions to examine optimal MPA siting and enforcement decisions.

III. Model

The model to examine MPA siting, sizing, and enforcement decisions contains several parts that are developed here: the spatial fish metapopulation model; the manager's optimization subject to budget constraints and villager behavior; the game theoretic model of villagers' choices of where to fish and how much labor to allocate to fishing; and a specific marinescape, parameter values, and model solution method.

Spatial Fish Metapopulation and Dispersal Setting. In common with much of the marine economics literature, a fish metapopulation structure on a grid with density dispersal defines the biological and spatial setting explored here. Fish stock changes in each site result from growth over time, harvest, and dispersal:

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

where $\boldsymbol{X_t}$ is a $J \times 1$ vector of fish stocks over fishing sites j at time t, $\boldsymbol{K}$ is a $J \times 1$ vector of site carrying capacities, $\boldsymbol{D}$ is a $J \times J$ dispersal matrix, and $\boldsymbol{H_t}$ is a $J \times 1$ vector of all fishers' harvest from each site j 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 growth at each specific site, with g indicating the intrinsic net growth rate. The steady state stock, $\boldsymbol{X_{SS}}$, occurs when $\boldsymbol{X_t} = \boldsymbol{X_{t+1}}$. 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).

Manager MPA Optimization. The manager selects a set of one or more sites, R, to define an MPA within the marinescape, and a level of enforcement in the MPA, to achieve a range of goals (G): maximizing total yield (including legal and illegal harvest), maximizing income (from fishing and non-fishing activities), maximizing MPA fish stock, and maximizing aggregate fish stock. The manager's optimal MPA policy – choice over sites, number of sites or total size, and level of enforcement – reflects the Nash equilibrium response of villagers to that policy. 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). Further, appropriate to an LMIC setting, limited budgets may prevent managers from implementing high enough enforcement levels to deter all illegal fishing in the MPA. The manager chooses a constant level of monitoring across all MPA sites that creates a probability of detection of illegal fishing in each site j, $\phi_j \in [0,1]$, such that $\phi_j = 1$ means that no illegal activity goes undetected while $\phi_j = 0$ implies that managers detect no illegal extraction (i.e. *de facto* open-access). Probabilities of detection below one can deter some or all extraction, with complete deterrence referring to a probability of detection that induces fishers to undertake no illegal fishing in that site. The manager can use some or all of an enforcement budget, B, to enforce across the set, R, of MPA sites:

$$\sum_{j \in R} c(\phi_j) \leq B \qquad [2]$$

Overall, the manager optimizes over the outcome of fishers' Nash equilibrium location and labor choices in response to the MPA at the steady state for fish stocks per site. She chooses one constant enforcement level ($\phi_{j\in R,}$) across the chosen MPA sites (in set *R)* to maximize the goal *(G)*, subject to the harvest levels that result from the Nash equilibrium distribution of fishers and fisher optimal labor allocations (***E***), the dispersal and fish regrowth relationships that produce the steady state fish stocks per site ($\boldsymbol{X_{SS}}$), and an enforcement budget constraint:

$$\max_{R,\phi_{j\in R}} G \quad s.t. \;\; \boldsymbol{E}, \boldsymbol{X_{SS}}, \sum_{j\in R} c\phi_j \leq \mathrm{B} \qquad [3]$$

Villager Equilibrium Choices. N identical villagers each maximize their individual income. Each individual villager makes a joint decision over the one site j in which he fishes and how he allocates his labor time across fishing labor in that site (l_{fj}) and wage labor (l_w). In making this decision, a villager recognizes that he must incur travel time (l_{dj}) to reach site *j*, that his decisions are subject to a time constraint *L* and to a one-site constraint on his fishing site choice, and that the *N*-1 other villagers will make their own choices over location and labor allocation:

$$\max_{j,l_{fj},l_w} [V] = \max_{j,l_{fj},l_w} \left[ph_j(1-\phi_j) + wl_w^{\gamma}\right]$$

$$s.t. \quad l_{fj} + l_{dj} + l_w \leq L\,,$$

$$h_j = l_{fj}x_j q_j\,, H_j = \sum\nolimits_{n_j} h_j \qquad [4]$$

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.

The enforcement parameter ϕ_j enters the fisher's objective function to reflect the probability that the manager detects illegal harvest. 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 fisher's harvest h_j depends on that fisher's fishing labor (l_{fj}), the fish stock in site j (x_j), and the site's catchability coefficient (q_j). This harvest amount does not directly depend on the number of other fishers that choose to fish in site j, although the total harvest H_j sums over all n_j fishers' harvests from site j. Rather, dynamic stock effects occur through the impact of harvest on the state variable x_j (the jth element of $\boldsymbol{X}$) in the steady state. Given this interaction of villagers' decisions in determining the steady state, a spatial Nash equilibrium defines the fishing locations for each villager, in which each villager has no incentive to move to another site nor to alter their optimally chosen labor allocation, with the *ex ante* identical villagers making different site and labor allocation decisions. The steady-state Nash equilibrium, denoted $\boldsymbol{E}$, that results from a set of parameters and policies defines the yield, labor, income, and stock in each site, in addition to the system-wide or aggregate outcomes.

Specific Spatial Setting, Parameters, and Solution. Spatially, we model a 3×2 grid (i.e. $J = 6$) with one fish subpopulation located at the centroid of each grid square (Figure 1). A single village located at the top of the leftmost column, nearest to the column-row (1,1) site, provides an asymmetric benchmark seascape with six biologically-identical fish sites that differ only in their distance from the village. Distance (l_{dj}) is simply the Cartesian distance from the village to the centroid of site j. A Matlab program numerically solves for all of the spatial Nash equilibria for the N identical fishers' sites and labor allocation decisions in the long-run biological steady state. Because we do not have full case-specific parameters, we use the parameter values in Smith et al. (2009) where our models overlap and choose other parameter values that, through parameter sensitivity analysis, provide the range of outcomes observed in our settings (Table 1). At these parameter values, no more than 12 villagers choose to fish, which leads us to use $N = 12$ as our village population.

IV. Results

The first section of results describes the optimal MPAs and related outcomes including fisher distributions and labor allocations for 4 manager types, in both 1-site constrained and no size constrained cases, across a range of budgets. That section also includes parametric variations of enforcement probabilities to inform the interpretation of the optimal decisions. The second section conducts two parameter experiments to further describe the impact of dispersal and distance costs on optimal MPA choices and presents two policy experiments using the model to characterize optimal MPAs in Costa Rica and Tanzania.

A. Optimal MPA location, size, and enforcement

Taking into account the reaction of villagers to an MPA, the manager optimally chooses an enforcement level and a set of sites that comprise an MPA to variously maximize total yield, total income, aggregate fish stocks across the marinescape, or MPA-fish stocks for a given budget. Figure 2 presents these optimal choices when the manager can choose the number and location of sites that comprise the MPA. Figure 3 presents the optimal choices when the manager is constrained to include only one site in the MPA. Figures 2 and 3 depict the number of villagers that fish in each site or that allocate all labor to wage work, denoted by the number of villagers in the village, in addition to the increase or decrease in the aggregate yield, income, and stock as compared to the no-MPA case. For a subset of budget levels and optimal equilibrium outcomes, Figure 4 provides additional information about the per-site fish stock and the per villager labor allocation for villagers fishing in each site. In all figures, the zero budget case corresponds to a no-policy, open-access setting based on the Nash equilibrium actions of villagers without an MPA, which implies a probability of detection ($\emptyset$) of zero throughout the marinescape. This section explores the drivers behind three primary findings from these results: the agglomerated spatial pattern of extraction with more fishers near the village; the differences in optimal MPAs across manager goals; and the impact of the budget constraint and costly enforcement on optimal MPA choices and villager decisions.

Pattern of fishing: Who fishes where and how much? In the benchmark case without an MPA, equivalent to a no-budget *de facto* open-access setting, villagers spread out across the marinescape but more fishers locate close to the village than far from the village, which results in lower stocks close to the village (Figures 2 and 4). Distance alone keeps fishers from the most distant site (3,2) despite high equilibrium fish stocks there, just as distance protects the interior of forests surrounded by encroaching/extracting villagers (Albers 2010; Robinson et al. 2011). This spatial equilibrium pattern of fishing and fish stocks reflects tradeoffs between within-site competition among fishers and the distance costs incurred to reach more distant fishing sites, combined with fish dispersal. 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. The interaction of these two effects, combined with fish dispersal, drives the choices of villagers over their fishing site and their allocation of non-distance labor to fishing or to wage labor. Those fishing in the site closest to the village (1,1) have the lowest travel costs but, due to the number of fishers in those sites, allocate the least time to fishing and the most to wage labor of all fishers (see Figure 4's labor allocation bars). Column 2 sites support more fishing than column 3, and only slightly less than column 1, due to dispersal relationships with three neighbors rather than two, as reflected in the higher number of fishers and fishing in (2,1) than in (1,2) despite (2,1) being slightly further from the village.

Villagers make their optimal fish-work labor allocation choices by comparing the marginal benefits of labor fishing in a particular site to the marginal benefits of wage work, which interact with distance costs, dispersal, and other villagers' actions. 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 (Figure 5). High wages, relative to returns to fishing, induce individual villagers to choose more wage work and less fishing labor, while higher wages induce some or all villagers to exit fishing and to specialize in wage labor. Consistent with stakeholder interviews in Costa Rica and Tanzania, villagers account for the cost of getting to fishing sites, which reflects the opportunity cost of time measured by the wage rate, when making their joint fishing site and labor allocation decision. Overall, distance costs, within-site stock effects, and dispersal patterns interact to generate a spatial pattern of fishing, which, at the base case parameterization, 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.

Achieving Ecological and Economic Goals. The model results suggest that managers optimally choose MPAs of very different size and configuration depending on their particular objective, including socioeconomic goals such as maximizing yield or income and ecological goals such as maximizing marinescape fish stock or within-MPA fish stock (compare across rows in Figures 2 and 3). For the unlimited budget case, the 4 manager types that face a 1-site constraint on their MPAs each choose a different site to locate the MPA (Figure 3). Among the size-unconstrained managers, only the MPA-stock and total stock maximizers employ identically sited MPAs at unlimited budgets, which differ from the optimal MPAs for the income and yield maximizers (Figure 2). Across budget levels, managers with ecological goals typically select larger MPAs than managers with socio-economic goals. Managers with socio-economic goals typically locate their multi-patch MPAs close to the village where the MPA restrictions solve some of the open-access over-extraction problem.

Although countries use MPAs both as fishery management tools and as ecosystem protection tools, some countries hope to achieve win-win scenarios between economic and ecological goals. This paper's model results contain no instances of an optimally defined MPA for one goal leading to increases in all 3 other goals as compared to the no-MPA case. In particular, no optimal MPAs create gains in both income and yield. That finding suggests that managers interested in improving villager welfare should interpret yield-focused analyses carefully. The MPA that maximizes income generates an increase in aggregate fish stocks relative to a no-MPA setting for a 1-site and multiple site MPA. In contrast, the MPA that maximizes stock increases income relative to the no-MPA scenario only in the 1-site MPA case, whereas it decreases income in the multi-site MPA case (Figures 2 and 3). Given the differences in optimal MPA size and location across various policy objectives, these findings suggest that managers and modelers should expect tradeoffs among improvements in stock, yield, and income rather than win-win situations.

Budget Constraints. 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 2). The MPA-stock maximizing manager maintains a large MPA across budgets, with the budget constraint determining the level of enforcement. For yield, income, and stock maximizing managers, lower budgets typically lead to smaller MPAs. The income-maximizing manager's MPA includes the near-village location at all budgets, with higher budgets allowing larger MPAs and enforcement levels that cause exit from fishing. 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. Both the income and yield maximizing managers achieve their optimal MPA at budgets of 25, with these managers choosing optimally to forego increasing enforcement at larger budgets. In addition, the managers with socioeconomic goals choose enforcement levels that do not completely deter fishing within the MPA. In contrast, the stock maximizing manager enlarges and changes location of the MPA with increasing budgets and uses both the location and enforcement level to generate complete deterrence and fisher exit wherever possible.

MPA Mechanisms for Changing Villager Behavior: Enforcement and Location. To achieve their various goals, managers choose a combination of the set of specific sites and enforcement to alter fishing behavior. Depending on the MPA pattern and intensity of enforcement, villagers respond to MPAs by altering their labor allocated to fishing, by changing their choice of fishing site, or by exiting fishing altogether. The location of the MPA enters villagers' decisions through the impact on distance costs on fishing site choice, in addition to dispersal's impact on returns to fishing in different sites. The level of enforcement in an MPA enters villagers' decisions by informing the expected returns from fishing across the marinescape.

The MPA-stock 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. In contrast, the stock maximizing manager consistently aims to create higher stocks by inducing exit from fishing, but the size and location of the MPA vary considerably across budget levels. For 1-site MPAs with an unlimited budget, that manager can impose a high enough level of enforcement to deter all fishing in the most-fished site (1,1) near the village and to induce two fishers to exit fishing and three to relocate to MPA neighbors (Figure 2, row 3). That near-village placement of the MPA imposes distance costs on the remaining fishers, which further reduces fishing labor and increases aggregate fish stocks. At a lower budget of 5, however, enforcement of an MPA next to the village cannot deter extraction there, which leads the stock maximizer to choose an MPA site, (2,1), where the budget induces one fisher to exit fishing, which has a large impact on aggregate fish stocks. Similarly, the stock maximizing manager for the multi-site MPA case varies the location and size of the MPA across budget levels, while maintaining an emphasis on inducing both exit and complete deterrence wherever possible (Figure2, row 3). Fishers respond to the MPA locations at a distance from the village by further aggregating near the village. At the low budget, however, the manager cannot enforce enough to completely deter extraction in any site and chooses to locate the MPA next to the village to partially solve the open access over extraction there and in the neighboring site (2,1). The stock-maximizing manager uses all of the available enforcement budget to deter extraction until villagers chose to allocate all labor to on-shore activities, at which point the enforcement budget no longer binds.

At high budgets, the income maximizing manager, like the stock maximizer, chooses MPA sites and sizes that lead to exit from fishing and to sites with complete deterrence. This manager's optimal MPAs, however, always include the near village site (1,1) where enforcement reduces the open access over-extraction problem enough to generate higher incomes (Figure 2, row 2). At budgets above 15, enforcement induces two fishers to exit and creates one site in the MPA with complete deterrence, (2,2). Dispersal from that perfectly enforced site leads a fisher to choose the most distant fishing site (3,2) that distance protects without this dispersal. The MPA in column 2 creates dispersal to columns 1 and 3, which induces fishers to spread out and further reduce overfishing in the site closest to the village. This manager's goal of maximizing income implies an emphasis on using enforcement and MPA location to encourage fishers to spread out to reduce income-depressing over extraction. The optimal MPA for maximizing income occurs at a budget of 25 and does not rely on complete deterrence in the MPA, with higher budget levels producing no further gains because increased enforcement decreases incomes.

In contrast, the yield maximizer's optimal MPAs never induce exit from fishing and, like the income maximizer's MPAs, do not completely deter harvest in the MPA. Instead, the yield maximizing MPAs spread fishers out, balancing reductions in congestion/stock effects with distance costs. A budget of 15 allows enough enforcement to induce the optimal level of fishing labor across the marinescape, with higher budgets going unspent. With this optimal MPA, the most distant site remains protected by distance and the near village site contains a high concentration of fishers and fishing labor. At low budgets, however, the yield maximizing manager cannot enforce at high enough levels in a near-village MPA to induce fishers to relocate. Instead, the manager optimally enforces an MPA in (2,2) that completely deters harvest there and creates dispersal patterns that induce some fishers to relocate, which spreads fishing labor and reduces negative stock effects.

Managers use both enforcement and MPA location to induce changes in villager behavior but the final complex outcomes of the optimal multi-site MPAs mask interactions of enforcement, distance costs, and dispersal that examining the 1-site MPA case elucidates. Parametric variation of enforcement levels from zero to 0.4 for the 1-site MAP reveal first, that as in the spatial forest economics literature, higher levels of enforcement deter more illegal extraction and that distance costs can augment low enforcement probabilities (Figure 6). For example, a near-village MPA in (1,1) requires a higher level of enforcement to completely deter harvest than the most remote site (3,2), which distance protects alone, or the second most remote site (3,1) which distance combined with an enforcement level of 0.075 fully protect. In the marine setting, in contrast to the terrestrial setting, dispersal also interacts with enforcement and distance in determining the impact of enforcement on illegal harvest. For example, the second closest site to the village, (1,2), requires the a lower probability of enforcement to achieve any level of illegal harvest than either of the more distant sites in column 2 because of column 2's dispersal connectivity.

Second, parametric variation of enforcement probabilities from zero to one for each one-site MPA reveals often non-monotonic relationships between enforcement and the goals for the marinescape (Figure 7). In these figures, sloped portions reflect marginal changes in illegal fishing labor in response to increased enforcement while jumps reflect fishers relocating to other sites or exiting fishing in response to increased enforcement. Each manager chooses the potential MPA site that provides the highest value of their goal for the enforcement probability their budget permits. All 3 manager types face regions in which increasing the probability of enforcement in a particular site leads to decreases in their aggregate goal, which implies that managers may not allocate all of their budget to enforcement. For example, the stock maximizing manager places the MPA in (1,2) for low budgets but does not increase enforcement above the 0.1 level even if the budget allows because that spending actually decreases aggregate stock. Only when the budget permits this manager to enforce at or above 0.33 does the manager switch the site of the MPA to (1,1) and use all the available budget on enforcement until complete deterrence at 0.37, after which additional enforcement spending simply has no impact. The yield-maximizing manager optimally locates the MPA in (1,1) at low budgets, in (3,1) at low-intermediate budgets, and in (2,2) at all higher budgets (Figure 7). An income-maximizing manager protects (1,1) at low budgets and (2,1) at all higher budgets, but without increasing the enforcement level beyond that achievable with low- intermediate budgets (Figure 7).

Despite the reality of incomplete enforcement in lower income country protected areas, implementation software and standard economic models tacitly assume that enforcement results in perfect compliance. That assumption leads to chosen MPAs generating fewer conservation benefits than intended due to unpredicted illegal harvests in the MPA. In addition, failing to consider incomplete enforcement in optimal MPA siting/sizing decisions leads to inefficient MPA choices. As compared to the optimal MPAs with a low budget (5), MPAs formed with an overly optimistic assumption of complete enforcement contain more sites – 6 rather than 2 sites for the stock maximizing manager and 4 rather than 2 sites for the income maximizing manager (with the yield maximizing manager's decision unaffected). The assumption of complete enforcement also belies the reality of PA managers' concerns over conflict between guards and illegal harvesters. If the number of illegal harvesters proxies for conflict, the optimal MPAs described here demonstrate that budget increases lead to different conflict levels for each manager type: for budgets of 5,15,25,35 and unlimited, the corresponding number of villagers fishing illegally in the MPA is 0,6,6,6,6 for a yield maximizing manager; 8,7,6,6,6 for an income maximizing manager; and 8,0,0,3,0 for a stock maximizing manager (Figure 2). Economic efficiency requires decisions based on the reality of incomplete enforcement – whether due to budget constraints or optimal marginal tradeoffs.

B. Parameter and Policy Experiments

To further understand the interactions of distance and dispersal in villager decisions and optimal MPA choices, this section undertakes analysis of no-dispersal and homogenous distance cost settings. Then, this section characterizes the settings in Costa Rica and Tanzania and uses the model to conduct policy experiments to inform management in those settings.

Parameter Experiments: Dispersal and Distance Costs

Dispersal. A model experiment with zero dispersal mimics a sedentary species case and demonstrates the impact of dispersal in determining fishing patterns. With zero dispersal and no MPA, two villagers choose to become wage specializers and the remaining 10 fishers spread out across space more than for the basecase (Figure 8). Without dispersal, villagers must incur distance costs to access fish stocks directly because the fish do not disperse to nearer village sites. The resulting equilibrium maintains the agglomeration of fishers near the village due to the distance costs but the most distant site contains one fisher. In this context, the yield-maximizing manager optimally locates an MPA near the village with enough enforcement to deter some fishing labor to reduce open access over-extraction yield losses, at all budgets. The income-maximizing manager always includes site (1,2) in MPAs, which induces one additional villager to exit fishing, and also selects the near village location at higher budgets to reduce over-extraction there. The stock-maximizing manager again aims to induce exit from fishing and complete deterrence of fishing where possible (Figure 8). Across budgets and manager types, the no-dispersal case's optimal MPAs contain fewer column two sites than the dispersal case because those locations cannot contribute to other sites through dispersal, which allows the enforcement-distance relationship to dominate the MPA location decisions. Yield and income maximizing managers reach their optimal configuration and enforcement level at moderately low budgets, with illegal fishing optimal in the MPAs.

Homogenous Distance Costs. Despite fishers' statements about the role of distance in choosing fishing sites, most of the MPA economics literature assumes either zero or homogenous distance costs. Here, setting all distance costs to the average distance from the village to a fishing site produces multiple equilibrium spatial distributions of fishers with two villagers becoming wage specializers due to higher costs and the remaining villagers spread out across sites because they face no trade-off between distance and congestion/stock effects (Figure 9). Four spatial equilibria result due to the allocation of 9 or 10 fishers over 6 sites with no "partial" fishers permitted: half of the equilibria have 3 wage-specializers and 3 fishers in each column; half of the equilibria have 2 wage-specializers, three fishers in the edge columns, and four villagers in the center column. That center column can support more fishing than the edge columns due to dispersal benefits from 3 rather than 2 neighboring sites, which also permits more fishers and fewer wage-specializers in the second set of equilibria for the no-budget cse (Figure 9; 2 equilibria presented, 2 others are mirror images with flipped rows). The yield maximizing manager uses this column's dispersal role in optimally siting an MPA in both sites of column two that results in a single equilibrium at all budgets; the dispersal from the MPA enables the marinescape to support more fishers in the edge columns and overall, which, contrary to most expectations from MPAs, reduces the number of wage-specializers and increases the number of fishers as compared to the no-MPA case. The income maximizing manager also focuses MPAs on the center column but chooses a high enough enforcement level at moderate budgets to cause two additional villagers to exit fishing, create complete deterrence and associated high levels of dispersal, and induce the remaining fishers to fish in the edge columns; and, at low budgets, uses a larger MPA that includes the center column but with lower enforcement to induce one fisher to exit. The stock-maximizing manager chooses relatively large MPAs and again aims to induce fishers to exit and to create sites with complete deterrence, always including the middle column in the MPA. Fishers' decisions reflect the lack of heterogeneous distance costs by spreading out across the marinescape while MPA managers' choices focus on taking advantage of the center column's dispersal role. Income and yield maximizing managers achieve their objective at moderate budgets, with the yield maximizing MPA containing optimal illegal fishing.

Overall. Removing either dispersal or heterogeneous distance costs from the marinescape setting leads to different optimal MPAs than the basecase and isolates the individual contribution of each aspect to the choice of MPA. Most economic MPA analyses consider only dispersal, which leads to MPA locations that focus on protecting sites that can contribute beyond the MPA through dispersal and to fishers spread evenly across the marinescape. Employing such an MPA in a setting of artisanal fishers that consider distance costs as part of labor allocation decisions may not achieve the desired outcomes as fishers tend to choose sites closer to the village rather than spreading out.

Policy Experiments: Costa Rica and Tanzania

Costa Rica's Caribbean coast MPAs: the Role of Wage. Costa Rica's Tortuguero National Park attracts many tourists, which has generated job opportunities and a high local wage. Many fishers report that they now fish less in response to the good wage opportunities and others have exited fishing for tourism positions (Madrigal et al., 2015). Still, Costa Rica's park managers focus on ecological outcomes and face limited budgets. Using these stylized facts for Costa Rica's focus on marine stocks, a low enforcement budget, and high onshore wage, the model finds large optimal MPAs with low enforcement levels. The model results find three wage specializers, a concentration of fishers and fishing near the village, and illegal fishing in the MPA (Figure 10). Just as in these stylized model results, maps of fisher locations near Tortuguero National Park reveal a pattern of highly congested near-shore fishing by people that allocate a large fraction of their time to onshore labor rather than fishing (Madrigal et al., 2015). Despite no direct policy to preserve incomes, these large but weakly enforced MPAs do not impose large income burdens on local people because Costa Ricans who limit or exit fishing replace their fishing labor time with high hourly wage jobs. As Costa Rica considers extending MPAs, both the ecological and economic impact of that expansion will rely on whether the onshore wage opportunities expand as well.

Tanzania: Poverty Alleviation and Conservation Goals. Tanzania's legislation defining marine parks requires management to provide both ecological and economic goals but these MPAs receive only small enforcement budgets and most MPA locations have very low wages. Using the model to determine an optimal MPA for maximizing incomes subject to a minimum stock constraint with a low budget reflects these stylized facts and produces an MPA at a distance from the village with fishers agglomerated near the village despite low wages implying low distance costs (Figure 10). The low wage results in income-maximizing MPAs being similar to yield maximizing MPAs, with few opportunities for win-win scenarios between income and stock goals. Given this struggle to find MPAs that improve stocks and incomes, Tanzanian managers are exploring MPA policies beyond no-take reserves that enforce access restrictions against non-local fishers while permitting local villagers to fish. Here, that scenario corresponds to enforcing a reduction in the total number of fishers rather than enforcing in particular locations in the marinescape. Using the basecase parameters, if enforcement can reduce fishers from 12 to 8, aggregate fish stocks increase by 11 percent and per local villager incomes increase by nearly 9 percent (Albers, et al., 2015). Given low budgets and difficulties finding no-take MPAs that increase both stocks and incomes, considering other MPA policies that permit local villagers to fish legally could help achieve Tanzania's dual goals for MPAs, and reduce conflict between nearby villagers and park managers. Instead, most MPA initiatives in Tanzania include entry fee-based payments or on-shore projects to provide fishers with alternative income-generating activities to account for poverty goals. Yet, Tanzania's projects and payments rarely incorporate any conditionality to create incentives to reduce fishing in exchange for benefits-sharing and alternative income-generating projects include few villagers, which limits their impact on fishing decisions and has led to conflict between marine park managers and the villagers left out of the livelihood projects (Albers et al., 2015; Robinson et al., 2014).

Overall. Our results and observations suggest that onshore labor opportunities can both mitigate the burden of MPAs and augment limited enforcement budgets in Costa Rica and Tanzania. No economic analysis exists, however, to describe the potential tourism response, and thus the labor opportunity response, to increasing the enforcement, size, or number of MPAs in Costa Rica or Tanzania. Neither country has explored opportunities to locate MPAs far enough from villages to increase the impact of low enforcement levels, as explored in the results above. Neither Costa Rica nor Tanzania makes decisions over siting or expanding MPAs with full recognition of the interaction of fisher decisions, enforcement, and the MPA location/size. Instead, both countries have based their initial MPA siting decisions on the ecological characteristics of the marine setting.

V. Further Policy Implications and Discussion.

This section considers the implications of the results described above for terrestrial and marine settings; for implementation of MPAs that permit some resource extraction and reduce conflict; and for future research.

Lessons Across Terrestrial and Marine Settings. The oft-remarked distinction between forests and fish focuses on the fact that trees do not move while fish do move, but similarities across settings permit managers in one setting to learn lessons from those in the other setting. First, potential extractors make distance or location decisions in both forest and marine settings, which implies that marine resource economics and policy can learn from the analyses of those decisions in terrestrial PAs. As in the marine results here, those analyses find that optimal PA decisions based on the spatial reaction of extractors to a PA permit more conservation per dollar due to efficiency gains from exploiting the relationship between enforcement probabilities and distance costs, which dispersal complicates but does not overturn. Second, the early emphasis of marine PAs on dispersal from MPAs to nearby fishable sites mirrors the terrestrial PA literature's recent move toward considering PAs within a broader landscape, where the PA and non-PA sites contribute both ecosystem services and inputs to rural welfare. Similarly, recent

REDD (reducing emissions from deforestation and forest degradation) studies demonstrate the potentially offsetting forest losses that occur when people respond to a protected forest with "leakage" of their forest resource demand to other locations or to markets. The leakage in the forestry context also proves important for aggregate marinescape benefits from MPAs when villagers relocate their fishing or exit fishing altogether. Third, terrestrial PA frameworks incorporate limited representations of resource/species movements in defining PA systems, which MPA analyses find critical. Overall, PA frameworks that incorporate explicitly spatial movements of both the resource and the extractors increase the efficiency of decisions for the siting, sizing, and enforcing PAs, especially in the context of limited enforcement budgets, incomplete enforcement, and rural poverty (Albers, 2010; Robinson, et al. 2011).

Beyond No-take Zones: IUCN Classifications and Conflict. Limited enforcement budgets in lower income country PAs 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). Within this modeling framework, costs of conflict could reflect the number of extractors or poachers caught in the PA. To avoid these costs, but still achieve their objectives, managers in lower 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, which might imply lower conflict costs as well (Pfaff, et al. 2014; Ferraro, et al. 2013). Future research to understand the actions of extractors in such 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 access restrictions through the IUCN classification to achieve both ecological and economic goals including low levels of conflict.

Ongoing and Future Research. This framework forms a foundation to explore other aspects of the socioeconomic and ecological settings of MPAs in lower 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 lower-income countries where fishers face labor allocation decisions and distance costs, and managers face enforcement costs, limited budgets, and a range of MPA goals. Managers achieve ecological goals with large MPAs at a distance from population centers, with enforcement that generates exit from fishing and complete deterrence where possible. Managers achieve socioeconomic goals with smaller MPAs located near harbors, with enforcement levels that induce fishers to spread out to avoid over-extraction. These MPAs often contain optimal – but illegal – fishing, even without binding budget constraints. MPAs aimed at maximizing aggregate yield rarely lead to increased incomes or stocks, which suggests tradeoffs among policy goals. 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 congestion stock effects. Marinescape outcomes respond to changes in enforcement levels in complicated, non-monotonic ways due to the interactions of distance, dispersal, onshore wage, and enforcement probabilities in determining villager's decisions about fishing labor and fishing location.

In terms of 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 lower income countries dramatically expanding MPA networks while also addressing poverty, managers that recognize the characteristics of artisanal fisheries avoid MPA policies that lead to unintended outcomes or to inefficient MPA choices. For example, on-shore wage opportunities may permit conservation benefits through fishery exit without burdens on local people, but many MPA analyses do not consider fishers' labor allocation decisions, which makes the impact of both MPA and wage policies difficult to assess. Similarly, MPA policies and analyses often aim at increasing fish yields, but yield-based MPAs can lead to lower levels of income. Countries that separate their conservation, fishery yield, and poverty alleviation policies miss an opportunity to recognize the links and tradeoffs among these outcomes in implementing MPAs. MPA choices and policies that assume near-perfect enforcement create inefficiently large and under-enforced MPAs that produce lower outcomes than those that reflect enforcement costs and the villager reaction to enforcement levels. The policy and academic focus on MPAs as no-take zones ignores the realities of costly conflict between resource-dependent people and MPA guards, and overlooks opportunities for less restrictive MPAs to improve ecological and economic outcomes, especially in settings with optimal harvests within MPAs described here. Overall, MPA decisions that do not reflect the spatial ecological and socioeconomic setting may impose larger than expected burdens on local people, produce low conservation values, and overestimate conservation and community benefits due to misrepresenting the fishers' reaction to the MPA in terms of illegal fishing, fishing site choices, and fishery exit.

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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

Figure 1: Spatial Setting.

Village

1,1	2,1	3,1
2,1	2,2	3,2

The spatial setting contains $J=6$ fishing sites in a grid with 3 columns and 2 rows and a village located onshore closest to the fishing site in column one, row one (1,1). The column-row pairs identify the specific site of each fishing site, j.

Figure 2. Optimal Size and Configuration of MPAs by Goal and Budget

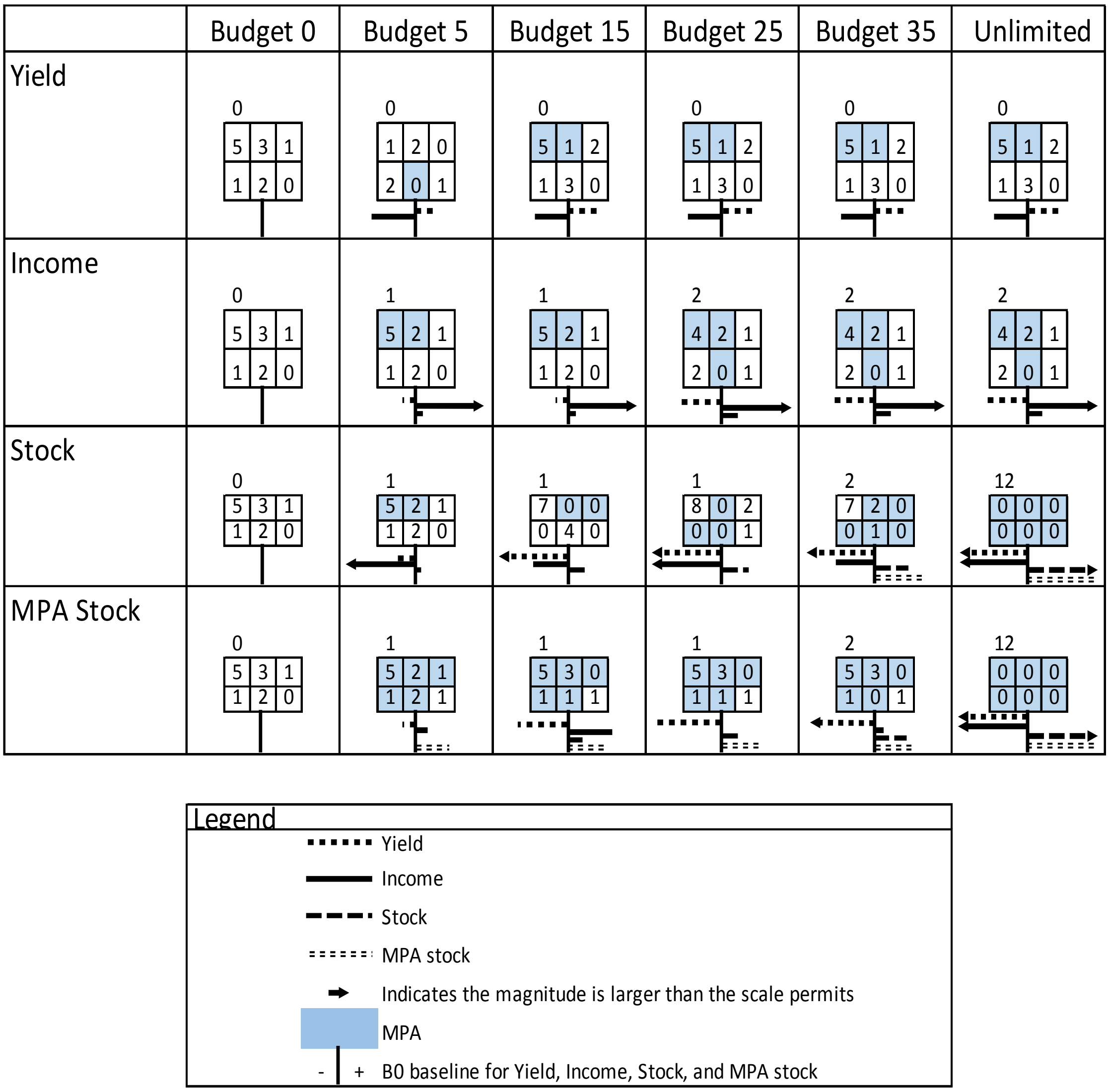
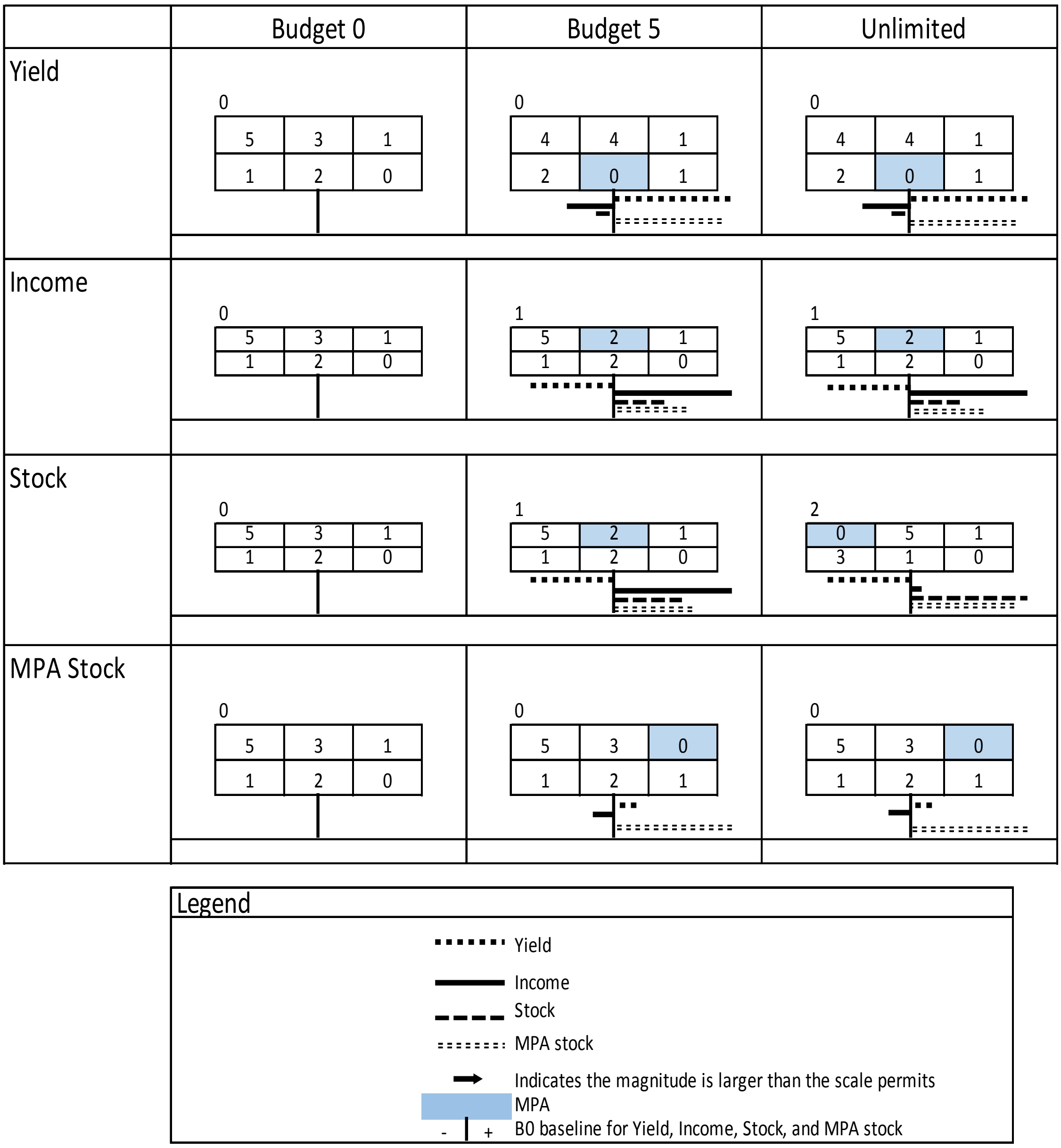


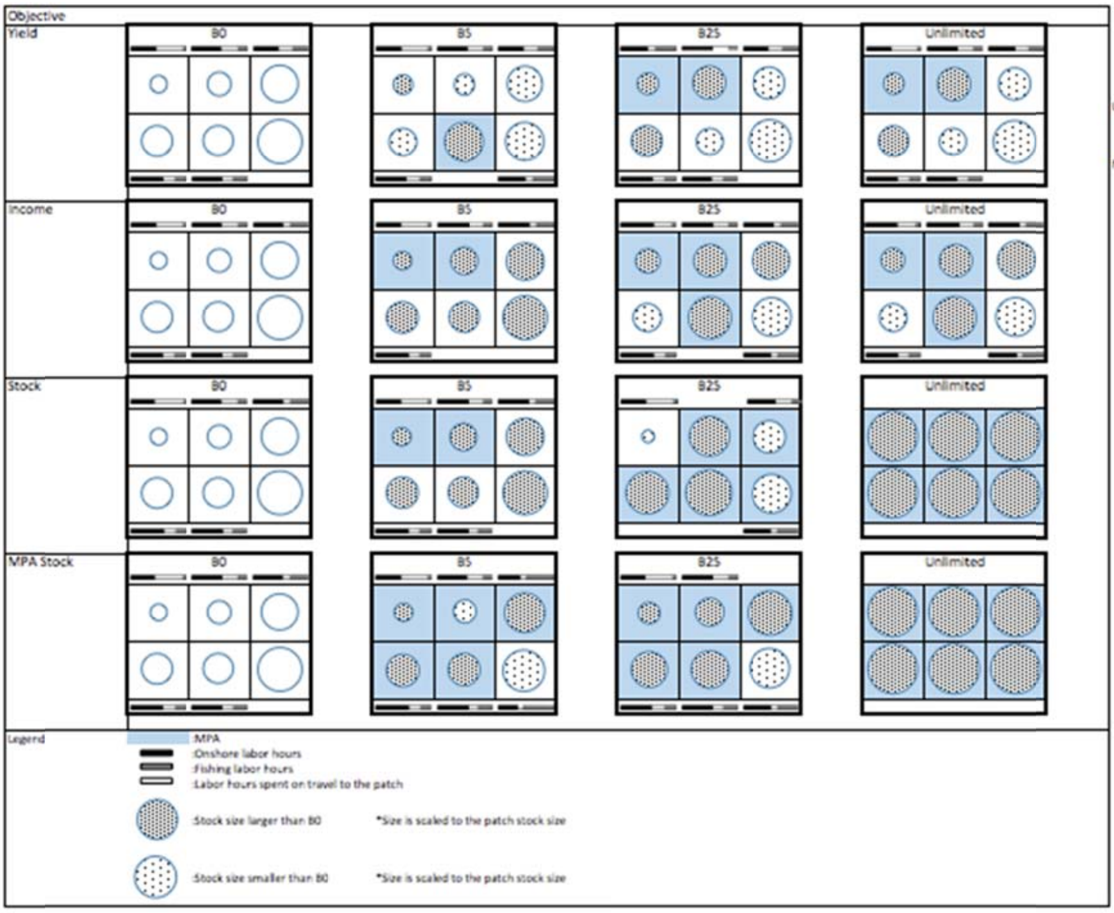
Figure 2. Each row of this table contains the optimal MPA configuration (MPA shaded) for that row's management goal at each column's budget constraint. The numbers in each fishing site depict the number of villagers fishing in that site while the number in the upper left of the marinescape represents the number of wage-specializers located in the village (who do no fishing). In some cases, more than one MPA configuration or distribution of fishers across sites proves optimal, which can reflect multiple Nash Equilibria or indifference between using excess budget to include a site in the MPA that requires no enforcement. The center line below the marinescapes marks a no-change point from the budget-0 case and the lines going to the right (left) indicate positive (negative) changes in the total yield, income, stock or MPA stock (with arrows indicating a large change beyond the scale).

Figure 3. Optimal Size and Configuration of a one-site MPA by Goal and Budget



This figure contains the optimal 1-site MPAs (shaded) for each of four management goals in both a constrained budget and unconstrained budget case. The numbers in each site indicate the number of villagers fishing there and the number above the left column is the number of wage-specializers. The center line below the marinescapes marks a no-change point from the budget-0 case and the lines going to the right (left) indicate positive (negative) changes in the total yield, income, stock or MPA stock (with arrows indicating a large change beyond the scale).

Figure 4: Per-fishing Site Labor Allocation and Stock Sizes



Columns contain the optimal MPA (shaded) for a budget of zero, five, 25, and unlimited for each manager type (rows). The bars above and below each fishing site reflect the per fisher labor allocations across fishing, onshore wage work, and time to fishing locations for all fishers in that site while the size of the circles reflects the fish stock size in that site and the circle's shading represents an increase (dense dots) or decrease (sparse dots) in the stock size compared to the zero budget no-MPA case.

Figure 5: Sensitivity to On-shore Wage.

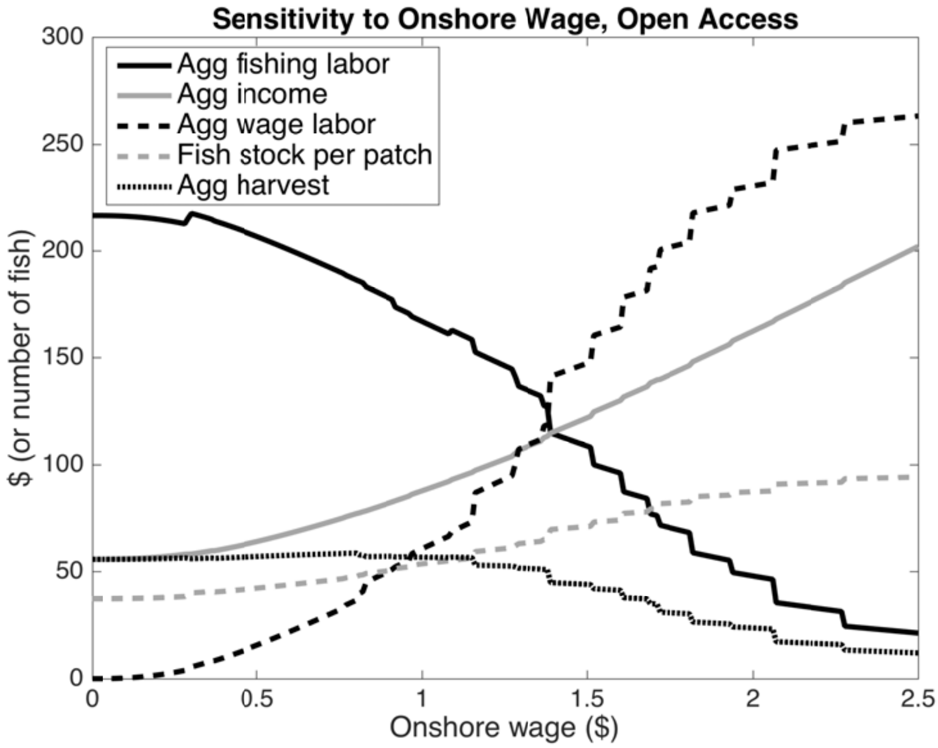


Figure 6: Response of illegal harvest to 1-site MPA enforcement probability.

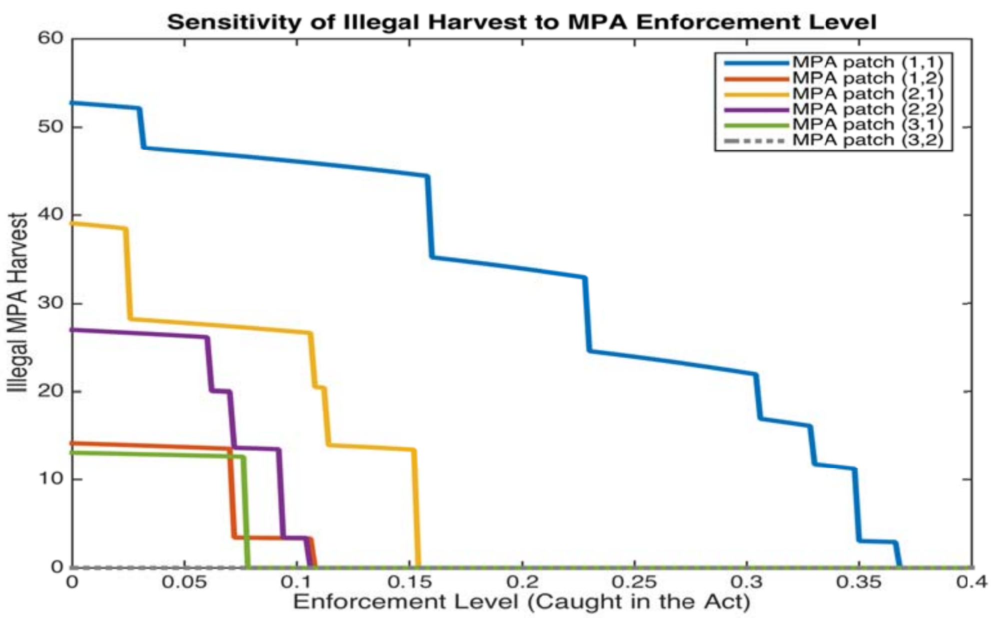


Figure 7: Relationship between Enforcement and Aggregate Outcomes, 1-Site MPAs

Each panel demonstrates how an aggregate outcome (stock, yield, income) varies with changes in the enforcement probability for each possible 1-site MPA.

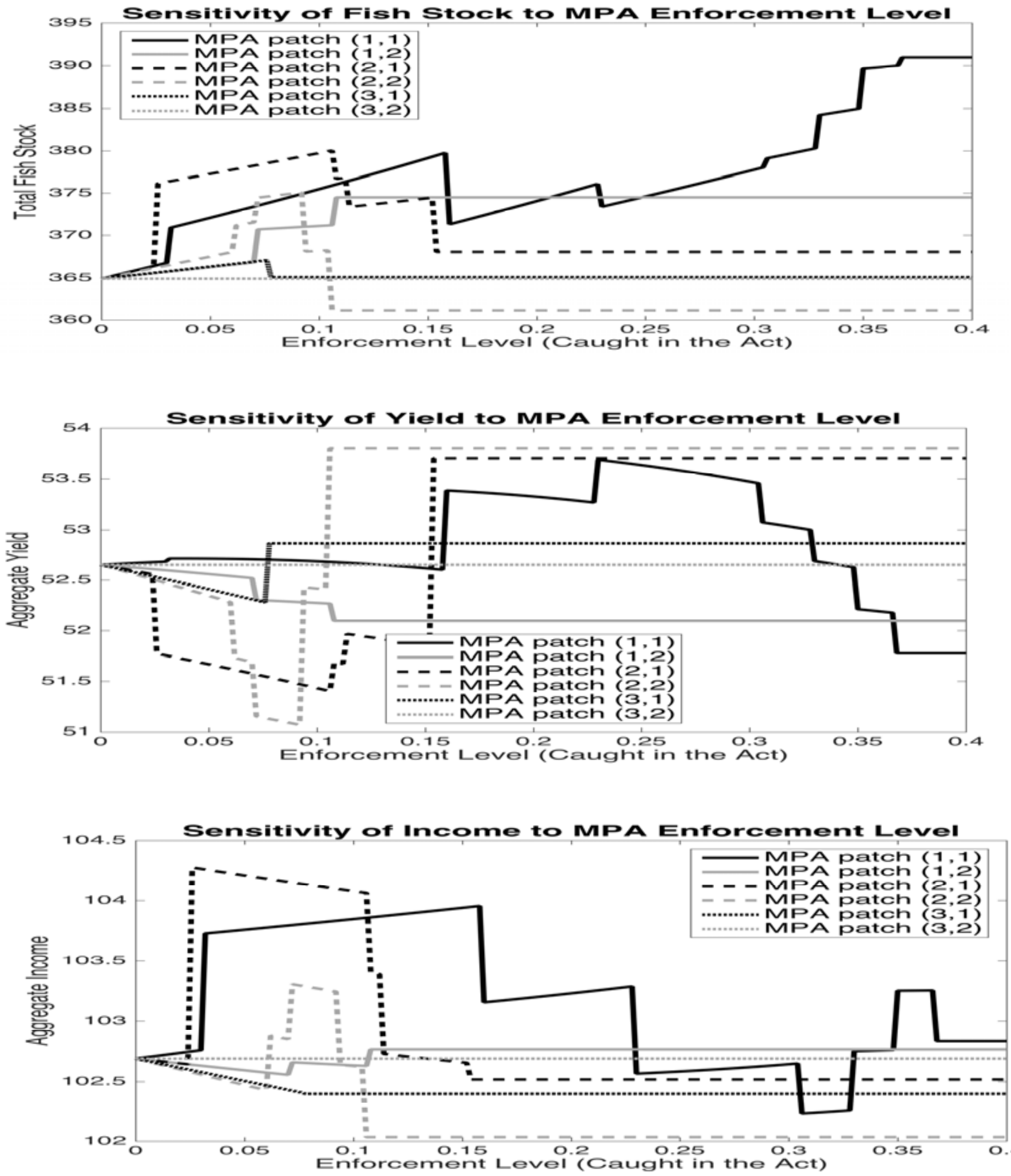
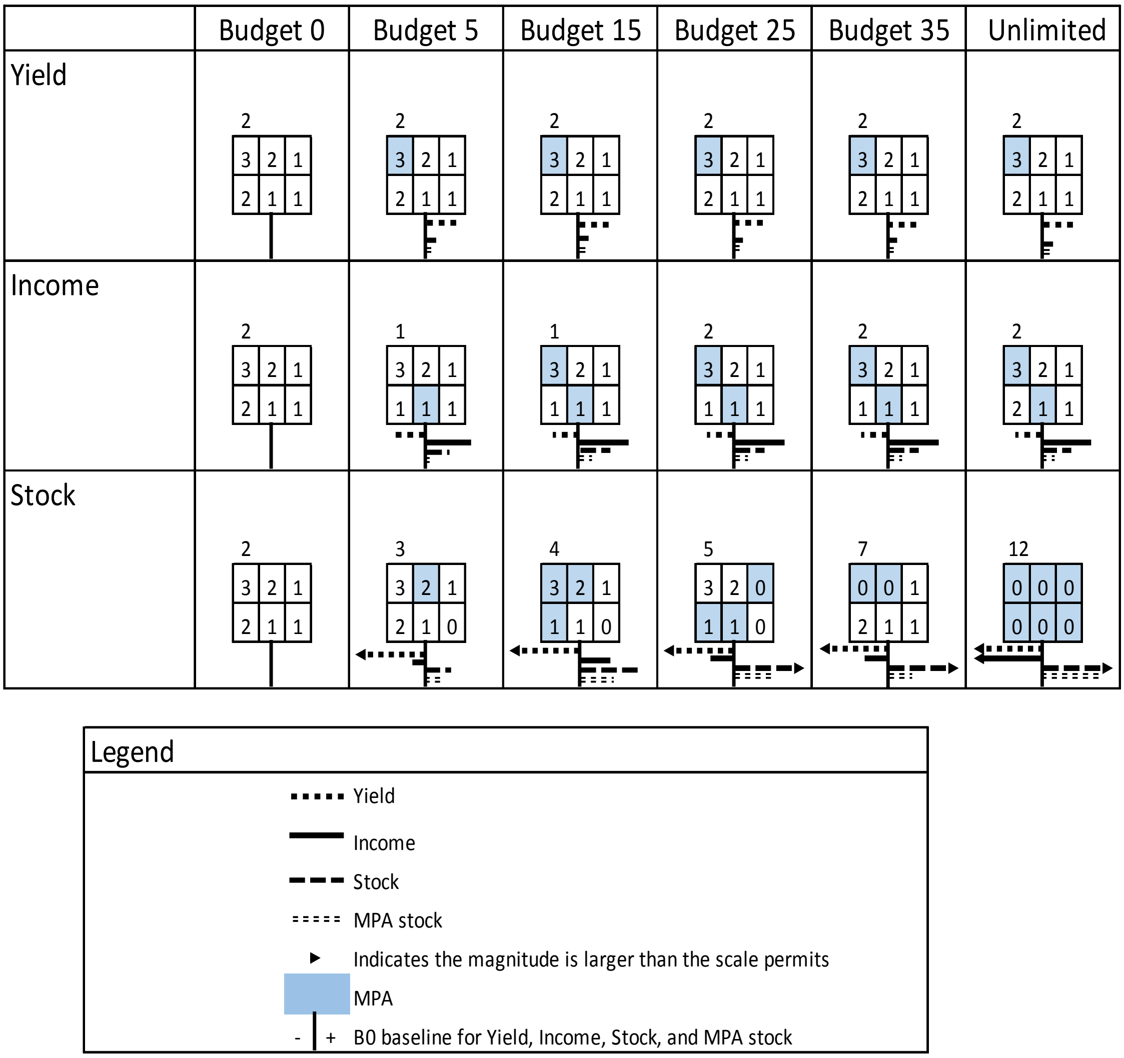
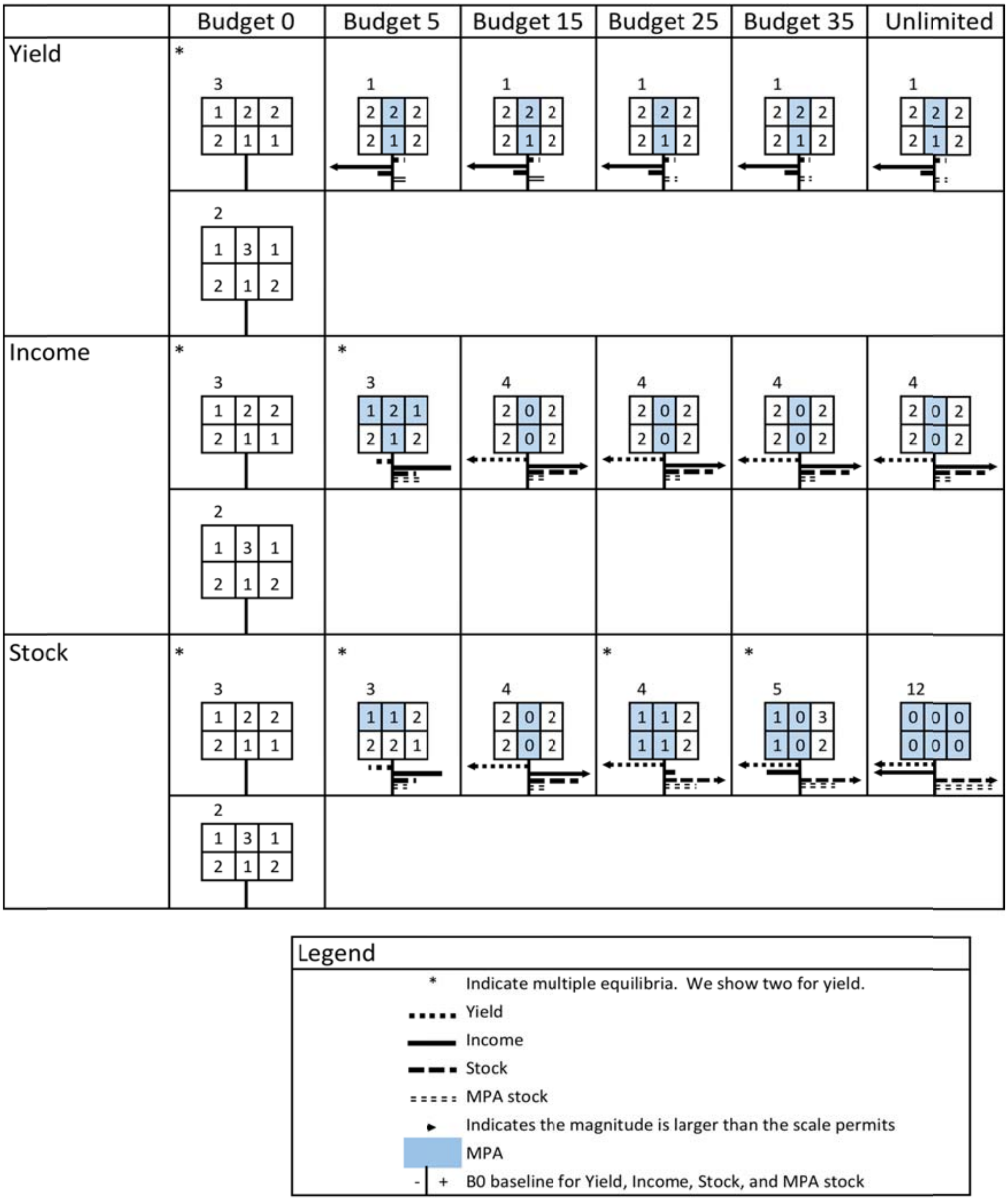


Figure 8: Optimal MPAs for No-dispersal Case.



The number in each of the six fishing sites in this figure depicts the number of villagers who fish in that site in equilibrium, while the number below the first column is the number of villagers who undertake no fishing and work for wage full-time. The bars below the marinescape indicate the changes from the zero budget case in the level of yield, income, and aggregate stock, with the length of the bar showing the magnitude and the direction showing the increases (right) or decreases (left).

Figure 9: Optimal MPAs for Equal-Distance Case.



Four equally valued spatial equilibria occur due, in part, to the lack of "fractional" fishers but we show two because the other two are mirror images. The bars below the marinescape indicate the changes from the zero budget case in the level of yield, income, and aggregate stock, with the length of the bar showing the magnitude and the direction showing the increases (right) or decreases (left).

Figure 10. Optimal MPAs for Stylized Costa Rican and Tanzanian Settings.

<table>
<tr><th>Costa Rica (high wage)</th><th>Tanzania (low wage; stock and income goals)</th></tr>
<tr>
<td>3
<table><tr><td>4</td><td>3</td><td>0</td></tr><tr><td>1</td><td>1</td><td>0</td></tr></table></td>
<td>1
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