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Marine Protected Areas in Artisanal Fisheries

A Spatial Bio-economic Model Based on Observations in Costa Rica and Tanzania

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Abstract

In many lower-income countries, the establishment of marine protected areas (MPAs) involves significant opportunity costs for artisanal fishers, reflected in changes in how they allocate their labor in response to the MPA. The resource economics literature rarely addresses such labor allocation decisions of artisanal fishers and how, in turn, these contribute to the impact of MPAs on fish stocks, yield, and income. This paper develops a spatial bio-economic model of a fishery adjacent to a village of people who allocate their labor between fishing and on-shore wage opportunities to establish a spatial Nash equilibrium at a steady state fish stock in response to various locations for no-take zone MPAs and managed access MPAs. Villagers' fishing location decisions are based on distance costs, fishing returns, and wages. Here, the MPA location determines its impact on fish stocks, fish yield, and villager income due to distance costs, congestion, and fish dispersal. Incorporating wage labor opportunities into the framework allows examination of the MPA's impact on rural incomes, with results determining that win-wins between yield and stocks occur in very different MPA locations than do win-wins between income and stocks. Similarly, villagers in a high-wage setting face a lower burden from MPAs than do those in low-wage settings. Motivated by issues of central importance in Tanzania and Costa Rica, we impose various policies on this fishery – location specific no-take zones, increasing on-shore wages, and restricting MPA access to a subset of villagers – to analyze the impact of an MPA on fish stocks and rural incomes in such settings.

Key Words: marine protected areas, spatial, Nash equilibria, bio-economic models, fisheries, hotspots

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1. Introduction

Marine Protected Areas (MPAs) are increasingly popular policy tools for protecting fisheries, marine biodiversity, and reefs, as reflected by the signatories of the Rio Convention on Biodiversity's commitment to protect at least 10% of coastal and marine areas within MPAs by 2020. The progress toward this goal has been varied, and most low- and middle-income countries, including Tanzania and Costa Rica, have yet to reach this goal. MPAs often have a central goal of protecting fisheries for harvest, in addition to protecting biodiversity and particular sites for recreation (Carter 2003). Therefore, MPAs explicitly recognize the role of the fish resource in livelihoods. In a low-income country context such as Tanzania, MPAs go even further, with efforts made to protect livelihoods through the implementation of alternative income-generating livelihood projects (Béné 2003; Gjertsen 2005; Silva 2006).

Much of the academic economics literature on MPAs centers on the impact of dispersal from no-take reserves on fishing outside of the fully-enforced no-take MPA, typically in the context of large-scale fisheries with fully-functioning markets and government institutions (Carter 2003; Hannesson 1998; Sanchirico and Wilen 2001; Smith and Wilen 2003). This literature rarely considers broader concepts of MPAs as applied in lower-income countries, labor allocation by villagers in small-scale artisanal fisheries, distance costs of travel time, and total income. Thus, the literature has less relevance for MPAs and small-scale fisheries in the challenging settings of lower-income countries.

After a review of the literature in Section 2, this paper develops a general spatial bio-economic model of a fishery with dispersal between fishing locations in a fish metapopulation in Section 3. A village of people allocate their labor between fishing and on-shore wage opportunities, and make fishing location decisions based on distance costs and fishing returns to

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generate a spatial Nash equilibrium of fishing location and effort. Varying the location of no-take zones in this fishery, under the assumption of full enforcement, produces information about the impact of a spatially-differentiated MPA on fish stocks, yields, and rural incomes in the long-run steady state, relevant to a lower-income country.[1] To examine issues of central importance in Tanzania and Costa Rica, we explore the role of on-shore wages and limiting the number of fishers with fishing rights within a broader, less restrictive MPA on biological and well-being outcomes. Section 4 presents the results from sensitivity and policy analysis and Section 5 discusses and interprets the results, with a brief conclusion in 5.5. An appendix contains tables of broader sensitivity analysis results for completeness.

2. Related Literature

Although many of the world's MPAs are located in lower-income countries, little of the economics literature focuses on the impact of MPAs on local fisher welfare, local people's incentives to cooperate, or changes in behavior. Exceptions include Gjertsen (2005), who uses an economic framework to examine the role of alternative livelihood projects in creating win-win situations while using MPAs to improve reef conservation and rural well-being. Similarly, Robinson et al. (2014) use an economic model of household behavior to determine how livelihood projects influence labor allocations to fishing and agriculture in the context of a depleted fishery contained in a new MPA. Other exceptions include Eggert and Lokina (2007); Béné (2003); and Allison and Ellis (2001). The impact of MPAs on small-scale fisheries is addressed in the policy, development, and marine resource literature, but typically without an economic decision framework (Mwakubo et al. 2007; Levine 2006).

The marine park setting in lower-income countries shares several characteristics with terrestrial protected area (PA) management in those countries. First, rural people's livelihoods often rely heavily on extracting resources from the parks, such as fuelwood, vegetables, and game (Falconer and Arnold 1989; De Beer et al. 1989; Poulsen 1990; Cavendish 2000), but PA managers are mandated to prevent this resource extraction through enforcement (Clark et al. 1993; Kaimowitz 2003; Wells and McShane 2004). The academic literature on terrestrial protected areas in developing countries emphasizes the impact of PAs on local people (Naughton-Treves et al. 2005; Wilkie et al. 2006) and mechanisms to create incentives for

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[1] Further analysis of this framework centers on incomplete enforcement. Similarly, other papers examine issues of gear restrictions and of alternative income-generating projects on fishing in MPAs (Robinson et al. 2014).

cooperation by local people (Ostrom 1990; Ostrom et al. 1994; Heinen 1996; Lane 2001), but little such research addresses MPAs in a developing country setting (exceptions include Carter 2003). A terrestrial park may place a burden on local people due to reduced access to resources in addition to negative externalities such as wildlife causing damages to crops and livestock, but can offset that burden through new local employment opportunities and tourism-related local wage increases (Robalino and Villalobos-Fiatt 2014). Similarly, in a marine setting, improved fish stocks within an MPA can lead to dispersal of fish beyond the MPA, which can offset the lost access to fishing in the MPA.

The resource economics literature provides models and empirical examinations of spatial aspects of MPAs and fisheries. These papers typically develop a marine-scape with patches of fish that interact with each other through dispersal in a metapopulation model. The academic research on MPAs has typically focused on how the creation of a no-take MPA, which closes an area or patch to fish harvest, affects fish populations and fish harvests within the MPA and in the broader region. Most papers reflect characteristics of fish biology, a key element being the dispersal of fish; dispersal may be density-dependent, from “sources” – which might be the MPA – to “sinks”, or through a “fountain” approach. Several papers find that the dispersal from a perfectly protected MPA is rarely large enough to completely offset the costs imposed on fishers of not being able to fish in the no-take MPA patch (Carter 2003; Hannesson 1998; Sanchirico and Wilen 2001; Smith and Wilen 2003).

3. Model

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. In contrast to that literature, here, fishers consider explicit distance costs from the village to the various fishing locations and make explicit labor allocation decisions in response to off-sea wages and MPA policies. Fish stock changes in each location occur through growth over time, harvest, and dispersal:

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

where X_t is a vector of fish stocks in each location in time t, K is a vector of carrying capacities, $G(X_t, K)$ is the net growth function, D is the dispersal matrix, and H_t is a vector of the sum of all fishers’ harvest in a location at time t. All vectors are $1 \times IJ$ (i.e., the dimensions of the closed system are $I \times J$), and each element of X_t, K, H_t refers to a specific $i \times j$ patch. The logistic growth function $G(X_t, K) = gX_t\left(1 - \frac{X_t}{K}\right)$ depicts the specific per-patch growth with g indicating the intrinsic net growth rate.

The $IJ \times IJ$ dispersal matrix D operationalizes the dispersal process as a linear function of fish stocks and densities of all patches (Sanchirico and Wilen 2001). For example, in a three-patch system with patches indexed {1,2,3}, the following dispersal matrix contains the information about dispersal across all possible combinations of the three patches:

$$DX_t = \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{bmatrix} \begin{bmatrix} X_{t1} \\ X_{t2} \\ X_{t3} \end{bmatrix} = \begin{bmatrix} a_1\left(\frac{X_{t2}}{K_2} - \frac{X_{t1}}{K_1}\right) + a_2\left(\frac{X_{t3}}{K_3} - \frac{X_{t1}}{K_1}\right) \\ a_1\left(\frac{X_{t1}}{K_1} - \frac{X_{t2}}{K_2}\right) + a_3\left(\frac{X_{t3}}{K_3} - \frac{X_{t2}}{K_2}\right) \\ a_2\left(\frac{X_{t1}}{K_1} - \frac{X_{t3}}{K_3}\right) + a_3\left(\frac{X_{t2}}{K_2} - \frac{X_{t3}}{K_3}\right) \end{bmatrix}$$

This matrix implies that

$$D = \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{bmatrix} = \begin{bmatrix} \frac{-(a_1 + a_2)}{K_1} & \frac{a_1}{K_2} & \frac{a_2}{K_3} \\ \frac{a_1}{K_1} & \frac{-(a_1 + a_3)}{K_2} & \frac{a_3}{K_3} \\ \frac{a_2}{K_1} & \frac{a_3}{K_2} & \frac{-(a_2 + a_3)}{K_3} \end{bmatrix}$$

Here, $\{a_1, a_2, a_3\}$ represent pairwise dispersal coefficients for each pair of patches. For example, a_1 affects dispersal between patches 1 and 2. Each column of D sums to zero, which guarantees (mechanically) zero net dispersal.

For an $I \times J$ grid, we generalize an $IJ \times IJ$ dispersal matrix, where each element is $d_{kl} = \frac{b_{kl}}{K_l}$.[2] In this paper, dispersal occurs between neighbors that share a boundary through rook contiguity and not across patch corners as in queen-contiguity. Numerators b_{kl} derive from a system-wide dispersal coefficient $m \in [0,1]$, where

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[2] We use *k* and *l* as indices to avoid confusion with the $I \times J$ dimensions of the system. Here, *i* and *j* refer to the row and column of a given patch; *k* and *l* index the patch itself.

- $b_{kl} = 0$, if $k \neq l$ and patches k and l are not neighbors
- $b_{kl} = \frac{m}{\nu_l}$, if $k \neq l$ and patches k and l are neighbors, where ν_l is patch l's total number of neighbors (i.e., $\nu_l = 2$ for a corner patch)
- $b_{ll} = -\sum_{k \neq l} b_{kl}$, constraining each column of D to sum to zero.

These conditions ensure, respectively, that direct dispersal only occurs between contiguous patches, that the same fish cannot migrate to multiple neighboring patches, and that the dispersal matrix maintains a constant aggregate fish stock.

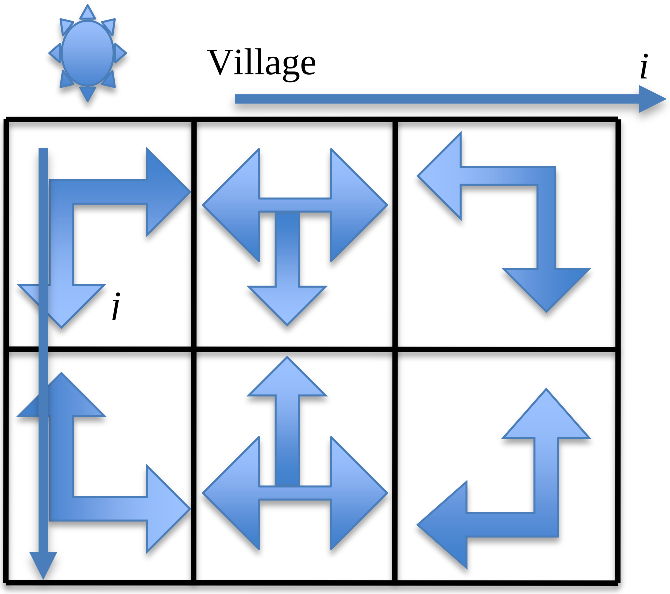
Identical villagers maximize income by allocating their labor time across fishing labor in location j (l_{fj}), travel time to location j (l_{dj}), and wage labor (l_w), subject to a time constraint and a one-location constraint on their fishing location choice:

$$\max_{l_{fj}} V = p l_{fj} x_j\, q_j (1 - \phi_j) + w l_w^{\gamma},\ \ s.t.\ l_{fj} + l_{dj} + l_w \leq L$$

where p is the price of fish, and fishing harvest is given by $l_{fj} x_j q_j$. Harvest per unit effort in location j depends on the fish stock in patch j (x_j) and on that location's catchability coefficient (q_j). Importantly, this rate of harvest does not directly depend on the number of other fishers in patch j, although the total harvest in a location j is the sum over all n_j fishers' harvests there. However, congestion effects occur indirectly through the effect of harvest on the state variable x_j (i.e., the jth element of X). ϕ_j is a policy parameter that equals 1 if location j is a fully-enforced no-take zone and 0 in the no-policy case. Finally, w represents the onshore wage rate, while $\gamma \in (0,1)$ allows for diminishing returns to onshore wage labor.

Spatially, we model a 3 ×2 grid with one fish subpopulation located at the centroid of each grid square. A single village is centered at the top of the leftmost column, providing a benchmark seascape with six biologically-identical fish patches (until the discussion of "hotspots" below) that differ only in their distance from the village (Figure 1). Distance (l_{dj}) is simply the Cartesian distance from the village to the centroid of patch j. A MatLab program solves for all of the spatial Nash equilibria for identical fishers' location and labor allocation decisions in the long-run steady state.

Figure 1. Schematic of Location of Fishing Village and Fish Patches with Rook Dispersal



Because we do not have full case-specific parameters, we use the parameter values in Smith et al. (2007) where our models overlap and choose other parameter values that, through parameter sensitivity analysis, provide the range of outcomes observed in our settings. At these parameter values, no more than 12 villagers choose to fish, which leads us to use 12 as our villager population. We depict specific cases particularly pertinent to Costa Rica and Tanzania by modeling the types of MPA policies often employed in those countries.

Table 1. Parameter Values

Description	Parameter	Value
No. of columns (moving along the coast)	I	3
No. of rows (moving out to sea)	J	2
Width of each column	-	4
Width of each row	-	3.5
Position of village by column	-	1
Intrinsic growth rate	g	0.4
Fish dispersal constant	m	0.4
Price of fish	p	1
Wage rate for non-fishing labor	w	1.25
Wage parameter (incr opp cost of time)	γ	0.6
Total time available per person	L	24
Catchability coefficient	$q_j, \forall j$	0.007
Carrying capacity	$K_j, \forall j$	100

4. Results

4.1 Open Access Fishery

The model's solution finds all the spatial Nash equilibria in fishing locations and effort at a long-run fish stock steady state. The equilibrium comprises the location of each villager, including those who undertake no fishing (located in the village); the number of villagers per location (illustrated in Figure for the base case with an open access fishery); the individual and total time allocated to fishing; travel time to fishing locations; wage labor; individual and total yield per location; and the steady state fish stocks per location. Fishers make tradeoffs between incurring distance (time) costs and competing for harvest with other fishers in any particular location. This section discusses results for the no-MPA or open-access fishery case in order to understand the decisions and outcomes in response to parameters before imposing MPA policy in the next sections.

In the benchmark case, those tradeoffs produce an equilibrium with the highest concentration of fishers in the fishing site closest to the village (1,1) and no fishers in the most distant site (3,2), despite the high equilibrium fish stock there (see Figure 2). In this open access situation, distance alone keeps fishers from fishing in patch (3,2), just as distance protects the interior of forests surrounded by encroaching/extracting villagers (Albers 2010; Robinson et al. 2011). The pattern of fisher location in the other sites reflects both distance costs and fish dispersal. For example, more fishers locate in (2,1) than in (1,2) despite the slightly longer distance from the village to (2,1) because the column 2 locations can support more fishers due to having dispersal relationships with three neighbors rather than two.

Figure 2. Equilibrium Spatial Pattern of Fishing Location Decisions

Village: 0

5	3	1
1	2	0

The number in each of the six fishing locations in this figure depicts the number of villagers who fish in that location in equilibrium, while the number above the first column is the number of villagers who undertake no fishing and work for wages full-time.

Distance costs and resource competition also contribute to a fisher's decision about how much time to allocate to labor. Distance costs incurred traveling to a fishing site reduce the labor time available for wage work or fishing. Congestion in a fishing site reduces the returns to marginal fishing labor. In the benchmark case, five fishers in (1,1) each undertake 11.7 hours of wage labor and 10.6 hours of fishing labor, while the two fishers in (2,2) work for 3.9 hours and fish for 13.5 hours. Our surveys in Costa Rica find this pattern of more fishers in near-village locations who undertake less fishing and more wage labor than their counterparts who fish in remote locations (Madrigal et al. forthcoming).

Varying wage, distance costs, and dispersal rates change both the amount of time fishers allocate to fishing and wage labor and the location of their fishing activities. If the onshore wage is increased, villagers fish less and undertake more wage labor. A sufficiently high wage induces some villagers to specialize in wage labor and refrain from fishing altogether, with the expected positive impact on fish stocks and incomes. A high wage implies high distance costs, which tends to discourage fishing far from the village and produces a more agglomerated pattern of fishers close to the village (Figure 3Figure 3). Similarly, low distance costs due to a low opportunity cost of time (reflecting a low on-shore wage) results in fishers more spread out across locations, in addition to increasing the amount of labor available for, and allocated to, fishing. With high rates of fish dispersal, fishers in near-village locations allocate more labor to fishing to take advantage of higher fish stocks there.

Figure 3. Impact of Wages and Dispersal Rates on Fisher Location

0

4	3	1
1	2	1

Low distance costs (3.5,3)

2

4	2	1
1	2	0

Low dispersal rates (*m*=0.3)

1

5	2	1
1	2	0

High wage (*w*=1.35)

0

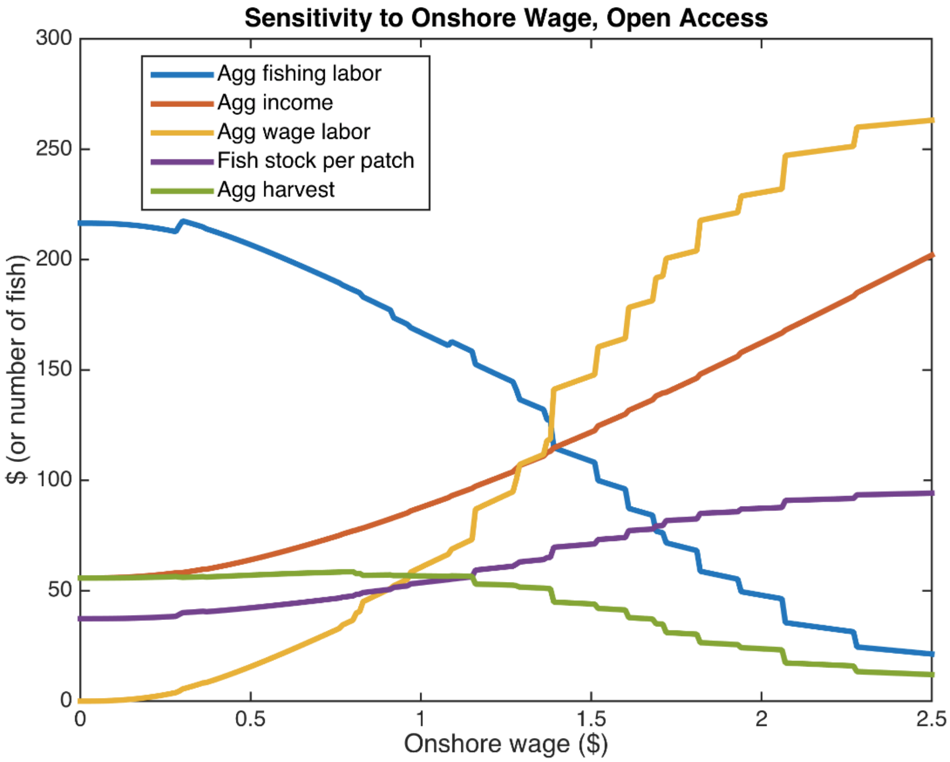
4	3	1
1	2	1

Low wage (*w*=1.15)

The number in each of the six fishing locations in this figure depicts the number of villagers who fish in that location in equilibrium, while the number above the first column is the number of villagers who undertake no fishing and work for wages full-time.

A comparative statics exercise of varying the on-shore wage from zero to 2.5 summarizes the impact of the on-shore wage on steady state equilibrium stocks and incomes (Figure 4). Tanzania is a low-income country with few wage opportunities for households living in fishing communities. Thus, for many Tanzanian fishers, the on-shore wage could be zero because they have no alternative livelihood opportunities. In this case, fish harvests are relatively high but overall incomes low. In Costa Rica, where the opportunity cost of labor is typically higher, these results suggest higher fish stocks, lower harvests, and higher aggregate incomes as compared to Tanzania for similar fish stock settings (Figure 4).

Figure 4. Sensitivity of Equilibrium Stocks and Income to On-shore Wage



Changes in wage and other parameters lead to marginal changes in labor allocation but also to discrete changes in the number of fishers in a given location, including the number of villagers who choose to specialize in wage labor. For example, at a low dispersal rate of 0.3 (compared to the base case 0.4), two villagers choose not to fish but rather to allocate all their labor to wage work. As compared to the benchmark, the reduction by one fisher in both (1,1) and (2,1) results in the remaining fishers in those locations increasing their individual allocations of fishing labor, but not enough to increase the total fishing effort in those locations (Table 2). Exploring responses to policy requires recognizing the interaction of marginal responses and discrete changes in decisions, and their impact on the equilibrium in the game.

Table 2. Summary Data for Various Open Access Fishery Equilibria

Scenario	Stock	Fish yield	Total income	# of non-fishers
Base case	365	52.6	103	0
Low distance	341	56.8	104	0
Low dispersal	383	50.6	105	2
High wage	384	51.3	110	1
Low wage	338	56.6	96	0

Setting the on-shore wage to zero permits a comparison with many other fishery/MPA models and isolates the spatial location decisions. Because the benchmark measures distance costs in terms of the opportunity cost of time, a zero wage implies zero direct distance costs, but time spent traveling to a distant fishing site still reduces the amount of labor remaining for fishing. With these parameter values, the Nash equilibrium has fishers evenly distributed across the six fishing locations, including the most distant site (3,2). Due to the lower levels of remaining fishing labor available in distant locations, and despite the even distribution of fishers across space, the equilibrium has decreasing fishing labor and increasing steady state fish stocks with distance from the village. The zero wage case leads to much lower steady state stocks in all locations than in the benchmark with a wage because all labor is allocated to fishing activities.

This analysis of the spatially-explicit open-access fishery contributes to the economics literature in several ways. First, the framework is spatial in terms of both the resource dispersal and the fishing location decisions, which allows the study to look at spatial patterns of resource quality and exploitation. Second, the inclusion of distance costs in the decision model interacts with more commonly-modeled stock effects to determine patterns of fish stocks and harvests. Third, the parameter analysis identifies the impact of the off-sea wage rate on both villager income and patterns of resource extraction and the interaction of dispersal rates and wage rates.

4.2 Marine Protected Areas as No-take Zones

In the economics literature, marine protected areas almost always represent marine reserves or no-take zones, as is typical in Costa Rica and in many high-income countries. In practice, reserves and no-take zones comprise a small fraction of MPAs, as in Tanzania, where an MPA may contain discrete no-take zones within larger areas where fishing is permitted but either limited to specific communities or to specific fishing technologies. Both Costa Rica and

Tanzania, in common with most lower-income countries, struggle to enforce various restrictions, and enforcement is rarely perfect.

In keeping with the economics literature, this paper explores the impact of perfectly enforced no-take zones in different locations to emphasize how the impact of the MPA differs depending on its location, with interactions with on-shore labor allocation decisions.[3] As such, this analysis provides a "best case" scenario, which can be used as a starting point to undertake further investigation into the implications of costly imperfect enforcement. Instead of defining an objective function for a manager, the analyses here vary the location and size of a no-take zone to explore the impact of the MPA's location on all aspects of the resulting equilibrium. Following the ecology literature's emphasis, these results inform discussion of MPAs creating win-win situations for fish yield and total fish stocks, with fish stocks as the conservation goal and yield representing the impact on fishers. Extending that literature to more fully represent the lower-income country case, the results also describe possible win-win situations between fish stocks and rural incomes.

The location of the MPA interacts with distance tradeoffs to determine the location of fishers and their aggregate fishing intensity in each patch. A one-patch MPA in the location nearest the village (1,1) induces two villagers to forgo fishing and specialize in wage labor. The remaining three fishers relocate to the patches that share a boundary with the MPA and one fisher moves from (2.2) to one of the MPA neighbor locations where fishers enjoy a high level of dispersal from the MPA (Figure 5).

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[3] To reflect the lower-income country enforcement difficulties, a related unpublished paper explores the levels of enforcement required to deter illegal fishing in MPAs and the impact of incomplete enforcement on yield, stocks, and rural incomes (Albers, et al., 2015).

Figure 5. Impact of Perfectly Enforced No-take Zone on Number of Fishers at Each Location

0

5	3	1
1	2	0

Base case

2

NTZ	5	1
3	1	0

No-take zone near village

1

6	NTZ	2
2	NTZ	1

Mid-column no-take zone

0

4	4	1
2	NTZ	1

No-take zone mid-distance

The number in each of the six fishing locations in this figure depicts the number of villagers who fish in that location in equilibrium, while the number above the first column is the number of villagers who undertake no fishing and work for wages full-time.

With fewer fishers overall, the total fish yield declines in response to the MPA, but, because the villagers who exit fishing undertake wage labor and the remaining fishers face less competition, total income increases in response to the MPA (Table). The commonly used metrics for a win-win situation, stock and yield, indicate that this MPA location does not generate a win-win. However, both stocks and overall villager income increase, suggesting an ecology-livelihoods win-win, primarily by reducing the number of fishers.

Table 3. Impact of MPAs of Different Locations and Size

MPA Location	Total Stock/ direction of impact		Total Yield/ direction of impact		Total Income/ direction of impact		# wage - only
None	364.92		52.65		102.69		0
(1,1)	390.97	+	51.78	-	102.83	+	2
(1,2)	374.51	+	52.10	-	102.76	+	0
(2,1)	368.09	+	53.71	+	102.52	-	0
(2,2)	361.13	-	53.81	+	102.03	-	0
(3,1)	365.09	+	52.87	+	102.40	-	0
(3,2)	364.92	0	52.65	0	102.69	0	0
Col.1	424.64	+	46.09	-	101.90	-	3
Col. 2	387.19	+	49.26	-	102.68	-	1
Col. 3	386.41	+	48.37	-	103.32	+	1
Row 1	456.20	+	39.38	-	102.30	-	5
Row 2	414.71	+	43.69	-	102.10	-	1

Each different possible location of a one-patch, fully-enforced no-take zone has a different impact on stocks, yields, and villagers' labor allocations, as villagers change their combinations of fishing location, fishing labor, and non-fishing wage work, but some general trends emerge. First, varying the location of the no-take zone has little impact on total village income, in part because villagers can substitute fishing labor for wage labor. The MPA leads to increases in the marine area's total fish stock at these parameter values for all but one MPA location, (2,2), where total fish stocks are lower as a result of the introduction of the no-take zone. The counter-intuitive biological outcome of a lower fish stock from an MPA in (2,2) derives from the location responses of fishers, which interacts with induced changes in the location and levels of dispersal. In this specific example, greater dispersal of fish from the protected patch (2,2) results in a higher stock in (3,2), which, under open access conditions, is not fished, making it a "natural" no-take zone. With a no-take zone in (2,2), this higher stock in (3,2) from dispersal overcomes the distance costs that provided natural protection for patch (3,2). Because the MPA in (2,2) induces fishing in the previously natural no-take zone, the MPA in (2,2) simply moves the no-take zone from (3,2) to (2,2) rather than creating an additional area of no-take, in addition to influencing where and how intensively villagers fish. This lack of additionality from the MPA results in a lower total fish stock from an MPA in (2,2) as compared to the open-access equilibrium. This MPA site demonstrates the importance of recognizing the reaction of fishers to MPA policies, and therefore the MPA's impact, as mitigated through interactions of fishing location decisions, labor allocation decisions, and dispersal.

Without considering the costs of establishing, enforcing, and maintaining an MPA, these results demonstrate that the impact of an MPA on yield, stock, and incomes depends on its location because of the reaction of the fishers in terms of where and how intensively they allocate their fishing labor. Early arguments for the use of MPAs suggested that, through dispersal, MPAs could increase stocks and yield in a fishery, creating a win-win. The results here find such a win-win by placing the MPA in (2,1) or (3,1) but not in other locations (Table). Though stocks increase, total yields decline with MPAs in any other location, except (2,2), which leads to both a lower fish stock and lower yield.

Given our focus on lower-income countries, an emphasis on yield as a measure of MPA success for fishers and the fishery appears somewhat misplaced. Rather, villagers' total income matters. Because villagers can make choices about on-shore and fishing labor, the difference between yield and income is non-trivial. In our results, a win-win-win situation, for stocks, yields, and income, never occurs for any MPA location (Table 3). Further, in our model, large (two patch) MPAs neither produce a stock-yield nor a stock-income win-win outcome (see appendix for more results). In settings in which villagers choose to allocate some or all of their labor to on-shore wage opportunities, that choice implies that some conservation effectiveness occurs through the discrete decision to forgo some or all fishing. For example, if the MPA is located in (1,1), there is the largest increase in fish stock of any one-location MPA, and of several larger MPAs. Total yield, however, is lower because some villagers displace some or all of their labor out of fishing and into on-shore work, which in turn results in higher total income. Although no other one-location MPAs lead to villagers becoming wage-specializers, all of the larger MPAs induce such specialization, which contributes to increasing fish stocks. However, for these larger MPAs, both total yield and income are lower than in a no-MPA setting (Table).

MPAs with no wage opportunities.

The no-wage benchmark equilibrium above, which is a proxy for a situation where there are no on-shore labor opportunities, has the fishers evenly dispersed over all fishing locations. When an MPA is introduced, fishers only relocate across space in response to the MPA, rather than also reallocating some of their effort away from fishing into wage labor. In all of the possible one-location MPAs, more fishers can be found in the rook-contiguous neighbors of the MPA, taking advantage of dispersal from the MPA, and fewer in non-contiguous neighbors. This relocation demonstrates the importance of dispersal from this type of perfectly enforced MPA in changing fisher decisions and in partially mitigating the impact of the closure on fishers overall.

For this specific calibration, we find that all but one of the one-location MPAs creates a win-win situation for stock and yield, and thus implicitly income, which now comes only from fish sales (Table 4). The outlier is the MPA in (3,1), which results in lower fish yields and thus lower fisher income, in part because it induces greater congestion than other MPA locations. The difference in the win-win locations between cases with and without on-shore wage opportunities implies that MPA siting/management for goals beyond ecological/resource improvements must assess the ability of fishers to make use of on-shore labor opportunities in defining the MPA and determining its impact on rural well-being.

Table 4. Impact of MPA Location and Size with Wage=0

MPA Location	Total Stock/ direction of impact		Total Yield/ direction of impact	
None	224.04		55.78	
(1,1)	261.75	+	57.89	+
(1,2)	249.15	+	56.52	+
(2,1)	244.58	+	57.32	+
(2,2)	244.76	+	57.35	+
(3,1)	243.68	+	55.38	-
(3,2)	243.62	+	56.04	+
Col.1	302.11	+	53.10	-
Col. 2	275.51	+	56.70	+
Col. 3	276.15	+	50.72	-
Row 1	334.26	+	49.01	-
Row 2	312.27	+	48.73	-

MPAs with “hotspots”

Typically, fish stocks are not evenly distributed across a marine area or across patches. Often, “hotspot” areas with high densities of fish develop while other patches contain few fish.

Varying the marinescape to reflect such heterogeneity permits the exploration of policies to place MPAs in such key "sources" of fish or elsewhere. For example, a hotspot in (2,1) without an MPA leads to a distribution with seven fishers directly on the hotspot (as compared to three fishers in (2,1) without a hotspot), three fewer fishers in (1,1), one fisher in the most distant location that receives zero fishing effort in the baseline above (with wage), and two locations with no fishing (Figure 1). Imposing an MPA on that hotspot increases total fish stocks and total income but decreases fish yield overall (Table 5). The inability to locate fishing in the hotspot due to the MPA leads fishers to enjoy the benefits of relatively high rates of dispersal from the hotspot MPA in the rook-contiguous locations closer to the village, but also induces some fishers to locate in previously unfished locations (3,1) and (2,2) (Figure 6). With this hotspot, if an MPA is introduced in any of the non-hotspot locations, fish stocks increase but total income falls. As in the cases without hotspots, depending on its location, the MPA can generate a win-win for stocks and yield or stocks and income, but not all three. Much of the ecological and economics literature assumes that any MPA will contain the hotspot itself, but these results suggest that goals beyond increasing stocks can lead to different location choices for the MPA.

Figure 6. Impact of Protecting a Hotspot at (2,1), Indicated by *s around the Number of Fishers in that Location

0

2	*7*	0
2	0	1

Base case

0

6	*NTZ*	2
1	3	0

No-take zone on hotspot

0

NTZ	*8*	0
3	0	1

No-take zone near village

The number in each of the six fishing locations in this figure depicts the number of villagers who fish in that location in equilibrium, while the number above the first column is the number of villagers who undertake no fishing and work for wages full-time.

Table 5. Summary Data with a Hotspot

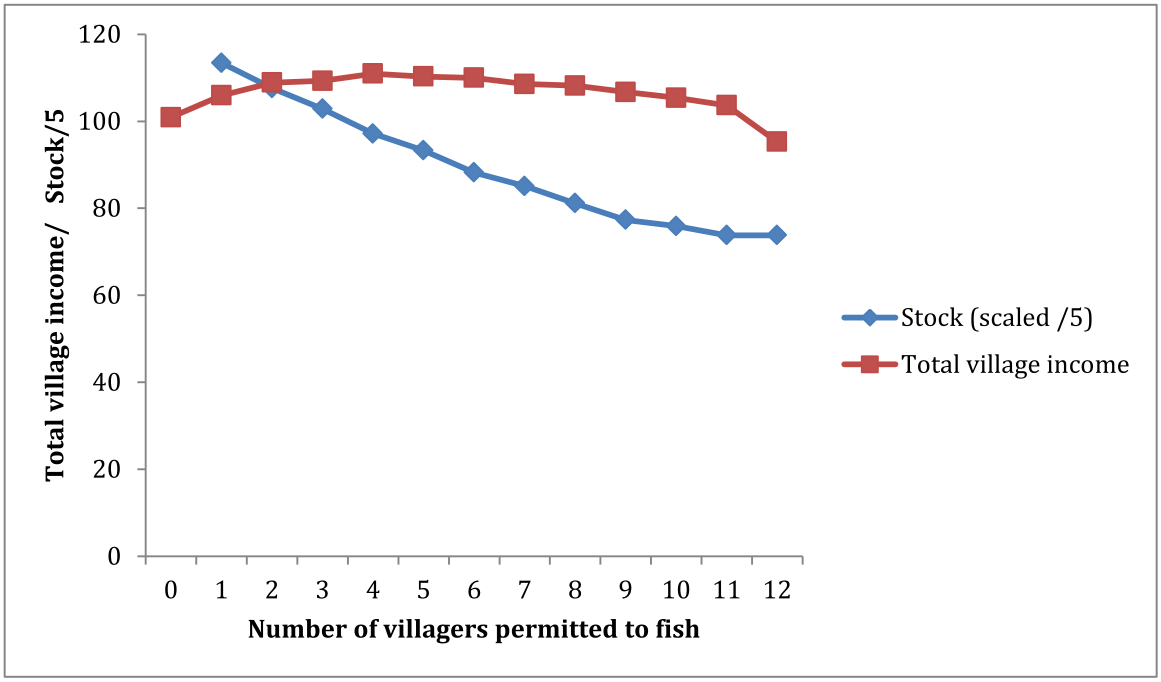
Scenario	Stock	Fish yield	Total income	# of non-fishers
Base case with hotspot in (2,1)	362	59.8	103.9	0
With MPA in hotspot (2,1)	467	57.4	104.2	0
With MPA near village (1,1)	371	60.2	102.7	0

Overall, this analysis of MPAs as no-take zones explores several ways in which MPA location matters for evaluating the impact of the MPA. In contrast to much of the spatial economics modeling literature about MPAs, this analysis shows how spatial parameters such as distance and non-spatial parameters such as wage interact with the MPA location and MPA size to determine the pattern of fishing, size and distribution of harvests and stocks, and labor allocation and incomes. The explicit modeling of the ability to choose non-fishing activities and the level of the wage in that activity proves especially important for determining the impact of the MPA on yield, income, and fish stocks. The hotspot analysis lends some support to the often tacit assumption that hotspots should receive priority for MPA locations when stock size is the primary goal of conservation policy.

4.3 Marine Protected Areas with Harvests and Access Restrictions

As in the case of terrestrial protected areas, ranging from parks/reserves to less restrictive areas with sustainable resource use, MPAs can vary in the level of restrictions imposed. Lower-income countries such as Tanzania often impose few or very small no-take zones within a larger MPA, and restrict the total number of fishers in the MPA rather than restricting their locations. In Tanzania, “insider” villages have fishing rights within the MPA while “outsider” villagers do not (Robinson et al. 2014). MPAs managed in this manner rarely enter the MPA economics literature. Representing this MPA policy within the modeling structure here involves varying the number of fishers with access rights and limiting the outsider villagers to wage labor only (Figure 7, with basecase parameters).

Figure 7. Total Village Income and Total Fish Stocks as a Function of the Number of Villagers Permitted to Fish



Not surprisingly, the greater the restriction on the number of fishers, the higher the stocks and the greater the fishing income per fisher as congestion declines. Total village income is greatest for an intermediate number of fishers, and lowest for larger and smaller numbers of fishers. With a large number of fishers, congestion in fishing locations dissipates most of the fishery rents. With very few villagers permitted in the fishery, labor time constraints prevent the dissipation of fishing rents. In that case, insider fishers are substantially better off than those without fishing rights. For example, when only one villager can fish, that villager receives 13.43 units of income, while non-fishers receive 8.41. With six fishers, each receives between 8.9 and 9.2 units of income, as compared to 8.41 for non-fishers. Thus, this type of access restriction to subsets of people creates clear winners and losers.[4] Further, if fewer than five villagers are permitted to fish, the village as a whole loses out through lost fishing rents.

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[4] Even with no MPAs or no access restrictions, winners and losers emerge. Fishers located close to the village face congestion that limits their returns to fishing despite the low distance costs there. Still, the differences across fishers by location in the equilibrium are small and derive from the discreteness and fixed costs of this framework. In addition, this framework does not provide an allocation tool to determine who will fish in which locations in equilibrium and the results can be interpreted as having a different person in each location in each period in the steady state to equate returns across people.

5. Discussion and Conclusion

This paper uses a spatially explicit bio-economic model of artisanal fishers' location and fishing effort decisions in a spatial Nash equilibrium to examine the impact of the location and type of MPAs on conservation and rural incomes. Using observations from Costa Rica and Tanzania to ground the analysis, the framework characterizes lower-income country settings by incorporating the distance costs associated with artisanal fishing across space, explicitly modeling labor allocation choices between fishing and on-shore opportunities, and considering both no-take zone MPAs and limited-access MPAs.

5.1 Location of No-Take Zones

Empirical fishery economic analysis and our interviews and surveys in Costa Rica and Tanzania emphasize the importance of distance costs in fisher location decisions both with and without MPAs. In contrast to most MPA economic models, the results here identify patterns of fisher locations and effort as a function of the distance of fishing locations from the artisanal fishing village. Distance costs drive a pattern of less fishing effort far from the village, which results in higher fish stocks in those locations, and more congestion near the village. Where distance represents a significant cost of extraction, some areas remain unharvested even in the absence of MPAs, just as in the terrestrial park economics literature, where distance itself provides protection.

The location of an MPA interacts with the fisher location decisions and the dispersal of fish to alter patterns of fisher effort and resource stocks, which determine the net impact of the MPA. An MPA located next to a previously distance-protected area can create enough dispersal to its neighbors to induce fishers to incur the distance costs and harvest in that previously unharvested location. In less extreme examples, fishers tend to locate in dispersed-to locations neighboring MPAs to capture the dispersal from the MPA, which resembles the phenomenon of "fishing the line." Some locations of the MPA, such as those close to the village, induce a subset of fishers to stop fishing and become wage-specializers. The specific location of an MPA also determines its impact on total fish stocks, total fish yield, and total income for the community. Our model illustrates explicitly that, whenever distance costs matter for fishers' location and effort decisions, the effectiveness and burden of the MPA depends critically upon its location with respect to the village.

Neither Costa Rica nor Tanzania have sited MPAs, or considered expanding existing MPAs, with full consideration of the interaction of fisher decisions and the MPA location/size. Instead, both countries have based their initial MPA siting decisions on the ecological characteristics of the fishery. Even the ecological outcome of an MPA depends on the reaction of people to that MPA, with the results here suggesting what that response looks like in terms of patterns of effort and impact on stocks, yields, and incomes. Our ongoing research considers how these results change when we no longer assume complete and costless enforcement of an MPA. In such a situation, distance and enforcement costs introduce additional complex interactions that are likely to be important in both Costa Rica and Tanzania given current low levels of enforcement throughout the MPA systems in each country.

5.2 On-shore Wage Opportunities, Community Income, and MPAs

Rather than making the classic assumption of some fixed cost and a zero-profit entry/exit condition for the fishery, this analysis explicitly models villager decisions over labor allocation to fishing or to on-shore wage work. When villagers have a non-zero opportunity cost of labor, some optimally choose to forgo fishing, while others allocate some labor to on-shore wage work. As the results above and in the appendix reveal, having the opportunity to work on-shore leads to different patterns of resource extraction, levels of fish harvest and stocks, and total income when compared to the no-wage case. With these large qualitative and quantitative differences between a no-wage and a wage setting, it could prove difficult to draw insight from the economics and policy literature that doesn’t incorporate the labor allocation decisions relevant in many lower-income countries.

Early MPA initiatives often predicted win-win scenarios resulting from MPAs in terms of improved total fish stocks and greater total yield, due to increased dispersal from the no-take zone offsetting the lost harvest in the MPA location. Several economics papers, including this one, describe the somewhat rare conditions under which that outcome occurs. Indeed, much of the terrestrial park literature emphasizes the burden on local villagers associated with establishing parks on land that had traditionally been a source of fuel and food. Even if both fish stocks and yields do increase, our paper has demonstrated that total village income may still decline. Income and yield respond differently to MPA locations, with a specific MPA location rarely generating a win-win-win in stock, yield, and income. Because the win-wins in stock and yield occur from different MPA locations than those from stock and income, generalizing about the likely impact of an MPA from the literature that focuses on yield rather than on income will create problems if the impact of the MPA on villagers derives from its impact on income as opposed to yield.

Costa Rica’s Caribbean coast receives many tourist visitors annually, which provides on-shore wage opportunities in the tourism sector in addition to jobs in agriculture and manufacturing. Current MPAs may have indirectly raised nearby on-shore wages due to an increase in visitors. In contrast, Tanzania's on-shore labor opportunities include far fewer tourism positions and lower wages than those in Costa Rica. The modeling results demonstrate that higher wages reduce the labor allocated to fishing and, even without MPAs, lead to higher fish stocks. High enough wages can induce villagers to become wage-specializers, which further reduces the pressure on fish stocks. Because Tanzania's MPAs face the dual goal of conserving marine systems and alleviating poverty, MPAs invest in alternative income-generating projects within villages, which could act to raise the local wage and reduce fishing, thus contributing to the conservation aim as well. However, such projects include relatively few villagers and relatively small fractions of villager time, which limits their impact on fishing decisions. Costa Rican MPAs face no such requirements to address local development goals, but the current MPAs draw enough visitors that the MPAs have indirectly raised the local wages. Many fishers now fish less in response to these opportunities and others have exited fishing for tourism positions (Madrigal et al. forthcoming), as predicted by the modeling results here. These results and the Costa Rican experience suggest that alternative income-generating programs that create opportunities with higher returns than those in fishing can be powerful marine conservation tools through their impact on labor allocation decisions. As a caveat, however, no economic analysis exists to describe the potential tourism response, and thus the labor opportunity response, to increasing the size or number of MPAs in Costa Rica or in Tanzania.

5.3 No-Take Zones or Restricted Access

The analysis here follows much of the economics literature on MPAs in analyzing no-take zones with an assumption of complete enforcement. In the lower income country context, enforcement costs prevent such perfect enforcement and MPAs do not generally imply no-take zones. The results here address the lower-income country context through focusing on labor allocation with/without a labor market, increasing marginal value of labor in non-fishing work, and artisanal fisher distance/costs, but leave the impact of incomplete enforcement (Albers, et al., in draft, 2015) and MPA policies such as gear restrictions (Robinson et al. 2014) to further research. Considering its importance to policy in Tanzania, however, the results here explore the impact on conservation metrics (fish stocks) and well-being (yield, income) of policies that place restrictions on who can fish within a broad MPA. Limiting the number of fishers, as in the "inside MPA villages" in Tanzania, results in different patterns of resource stocks as compared to no-take zones but can have a large impact on both conservation and villager well-being. This type of policy may be easier to enforce than no-take zones but it raises issues of equity because

Tanzania’s “outside MPA” villagers capture no benefits from the MPA, while inside-MPA villagers receive improved yields due to lower levels of competition for the fish resources.

5.4 Realities in Tanzania and Costa Rica

In Tanzania, MPA law states that managers must address conservation goals in addition to poverty alleviation in and around MPAs. Only very small sections of MPAs are delineated as no-take zones, with those areas typically representing small coral reefs or other sensitive sites. Across all the MPAs, managers and villagers alike report that the MPA undertakes very few patrols to enforce the no-take zones. Rather, the managers engage in enforcing gear restrictions and access restrictions in the broader areas of the MPAs, but face limited budgets for that enforcement. In Mnazi Bay Ruvuma Estuary Marine Park, managers have not been able to implement their plan to restrict fishing to inside MPA villagers with appropriate gear, in part because family ties between insider and outsider villages and boat rental from insider villagers complicate the insider-outsider delineation (Robinson et al. 2014). In Mafia Island Marine Park, villagers report that enforcement has declined in recent years and that fishers from the mainland regularly harvest in protected areas, which they blame on reduced funding for enforcement and on payoffs by mainlanders to local officials. Managers and villagers in the new Tanga Marine Park report similar corruption issues through which dynamite fishers receive information about impending patrols. Although the insider village access could be successful in meeting Tanzania’s MPA goals, the lack of funding for enforcement and of well-established management practices limit the impact of Tanzania’s MPAs.

Of Tanzania’s marine parks, only villages in or near Mafia Island Marine Park appear to capture many benefits in terms of tourism-related work, and wages and agricultural productivity in these areas remain quite low. Viewed through the lens of the results here, that low-wage scenario implies that perfectly enforced MPAs can be a large burden for local people because people cannot allocate their effort away from fishing. Tanzania’s poverty alleviation programs include alternative income-generating projects that can pull villagers out of fishing if they are high enough in value, but those projects tend to include relatively small numbers of villagers.

In Costa Rica, marine park managers impose no-take zones on fishing in all areas of the park (ocean and canals) but permit non-consumptive guided tours. Scarce personnel and resources for monitoring limit the enforcement of such regulations by governmental authorities. Managers report a system of enforcement that relies heavily on receiving informational tips about illegal activities rather than on patrols. The tours and related tourism opportunities in Tortuguerro Marine Park, however, provide wage-work opportunities at a rate that more than competes with fishing and generates those jobs for a large number of local people. The lack of enforcement of MPA rules is partially offset by the draw of the on-shore labor opportunities, which, as in our modeling results, encourages people to reduce or forgo fishing, thereby reducing fishing pressure in the MPA, increasing fish stocks, and increasing local incomes. Whether that tourism wage impact will be large in response to expansions of MPAs as no-take zones in other regions remains an open question.

5.5 Final Remarks

Stemming from research on the impact of terrestrial protected areas on forest stocks and on rural villagers, this research examines the labor allocation decisions of artisanal fishing villagers in response to MPAs. Given the rapid expansion of various types of MPAs in lower-income countries, this modeling effort, informed by fisher and manager interviews, identifies important aspects of the interaction of MPA siting decisions and fishing decisions that determine both the success of MPAs in protecting fish stock and the impact of MPAs on rural communities. Because artisanal fishers face distance costs, the location of the MPA partially determines its impact on stocks, yields, and income. Some locations solve the congestion or overfishing problem by forcing villagers to spread out over space. In some cases, those distance costs deter all harvest in some areas, which implies that locating an MPA there has no impact on fish stocks, yields or incomes. MPAs place less of an income burden on villagers in a context of high on-shore wage opportunities to which villagers can allocate labor rather than relocating in response to an MPA, as occurs in a no-wage labor setting. In determining the impact of MPAs in lower-income settings with villagers who participate in fishing and other income-generating activities, the MPA’s location has different, and often opposite, effects on villager income versus fishery yields. This difference demonstrates that models that consider only yield may well underestimate and misrepresent the impact of an MPA on rural people. Policymakers with concerns for rural welfare, such as those in Tanzania, must define whether their goals are based on income and not yield.

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Appendix. Results from Sensitivity Analysis

For completeness, this appendix includes further parameter sensitivity analysis and policy scenarios not included in the text of the paper. Figure/Table A1 shows univariate parameter sensitivity analysis, keeping all other baseline parameters constant. Figures/Tables A2-A7 show all 42 permutations of single-patch no-take zones (NTZ) and single-patch hotspots (where $\boldsymbol{K_j = 200}$ for the hotspot j, and $\boldsymbol{K_j = 100}$ for all other patches). Asterisks indicate the hotspot in each figure. Figures/Tables A8-A11 include solutions to the model for various NTZ values at different wage levels (with all other parameters unchanged from the baseline). Finally, Figures/Tables A12-A14 show results from varying the population of potential fishers from 1 to 12, at different wage levels (with all other parameters unchanged from the baseline).

Consistent with the figures above, these appendix figures show the number of fishers choosing to fish in each patch of the 3X2 grid in equilibrium. The number at the upper left denotes the number of fishers (out of 12) who choose to specialize in wage labor in equilibrium. In a few cases, the parameter or policy setting produced multiple Nash equilibria. For these cases, we report the average results, assigning an equal probability weight to each possible equilibrium.

Figure A1. Parameter Sensitivity Analysis – Equilibrium Location Choices

0

4	3	1
1	2	1

Low distance costs [3.5,3]

1

5	2	1
1	2	0

High distance costs [4.5,4]

4

3	3	0
1	1	0

Low growth rate ($g = 0.3$)

4	3	1
2	2	0

High growth rate ($g = 0.5$)

2

4	2	1
1	2	0

Low dispersal ($m = 0.3$)

0

5.5	2.5	1
0.5	2.5	0

High dispersal ($m = 0.5$)

1

5	3	0
1	2	0

Low catch rate ($q_j = 0.006$)

0

4	3	1
1	2	1

High catch rate ($q_j = 0.008$)

0

4	3	1
1	2	1

Low wage ($w = 1.15$)

1

5	2	1
1	2	0

High wage ($w = 1.35$)

0

4	2.5	1.5
1	2.5	0.5

Low gamma ($w = 0.55$)

4

4	2	0
1	1	0

High gamma ($w = 0.65$)

Table A1. Parameter Sensitivity Analysis – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
Base case	364.9	52.7	102.7	0
Low distance	341.1	56.8	104.0	0
High distance	380.8	51.2	102.7	1
Low growth	382.1	37.5	103.1	4
High growth	383.2	63.1	106.3	0
Low dispersal	383.4	50.6	105.0	2
High dispersal	362.8	53.8	103.1	0
Low catch rate	417.0	45.6	101.8	1
High catch rate	314.2	57.4	103.0	0
Low wage	338.0	56.6	96.4	0
High wage	383.9	51.3	110.4	1
Low gamma	328.0	56.5	93.7	0
High gamma	437.5	42.3	119.5	4

Figure A2. NTZs with Hotspot in Patch (1,1) – Equilibrium Location Choices

0

7	1	1
0	3	0

Hotspot (1,1)

2

NTZ	5	1
3	1	0

Hotspot (1,1); NTZ (1,1)

0

7	1	1
NTZ	3	0

Hotspot (1,1); NTZ (1,2)

0

8	NTZ	1
0	3	0

Hotspot (1,1); NTZ (2,1)

0

7	2	1
1	NTZ	1

Hotspot (1,1); NTZ (2,2)

0

7	2	NTZ
0	2	1

Hotspot (1,1); NTZ (3,1)

0

7	1	1
0	3	NTZ

Hotspot (1,1); NTZ (3,2)

Table A2. NTZs with Hotspot in Patch (1,1) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
No policy	375.3	56.2	104.6	0
NTZ (1,1)	491.6	54.6	104.2	2
NTZ (1,2)	375.3	56.2	104.6	0
NTZ (2,1)	388.9	54.3	104.8	0
NTZ (2,2)	382.4	55.2	104.6	0
NTZ (3,1)	381.1	55.3	104.4	0
NTZ (3,2)	375.3	56.2	104.6	0

Figure A3. NTZs with Hotspot in Patch (1,2) – Equilibrium Location Choices

0

2	4	1
5	0	0

Hotspot (1,2)

1

NTZ	5	1
5	0	0

Hotspot (1,2); NTZ (1,1)

0

6	2	1
NTZ	3	0

Hotspot (1,2); NTZ (1,2)

0

4	NTZ	2
4	2	0

Hotspot (1,2); NTZ (2,1)

0

2	4	1
5	NTZ	0

Hotspot (1,2); NTZ (2,2)

0

2	4	NTZ
5	0	1

Hotspot (1,2); NTZ (3,1)

0

2	4	1
5	0	NTZ

Hotspot (1,2); NTZ (3,2)

Table A3. NTZs with Hotspot in Patch (1,2) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
No policy	370.0	57.5	102.7	0
NTZ (1,1)	386.4	58.8	104.2	1
NTZ (1,2)	474.6	55.0	103.9	0
NTZ (2,1)	375.8	59.3	103.7	0
NTZ (2,2)	370.0	57.5	102.7	0
NTZ (3,1)	366.8	58.4	102.9	0
NTZ (3,2)	370.0	57.5	102.7	0

Figure A4. NTZs with Hotspot in Patch (2,1) – Equilibrium Location Choices

0

2	*7*	0
2	0	1

Hotspot (2,1)

0

NTZ	*8*	0
3	0	1

Hotspot (2,1); NTZ (1,1)

0

3	*7*	0
NTZ	2	0

Hotspot (2,1); NTZ (1,2)

0

6	*NTZ*	2
1	3	0

Hotspot (2,1); NTZ (2,1)

0

2	*7*	0
2	NTZ	1

Hotspot (2,1); NTZ (2,2)

0

2	*7*	NTZ
2	0	1

Hotspot (2,1); NTZ (3,1)

0

2	*7*	0
2	1	NTZ

Hotspot (2,1); NTZ (3,2)

Table A4. NTZs with Hotspot in Patch (2,1)– Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
No policy	362.1	59.8	103.9	0
NTZ (1,1)	370.7	60.2	102.7	0
NTZ (1,2)	385.4	55.5	102.7	0
NTZ (2,1)	467.3	57.4	104.2	0
NTZ (2,2)	362.1	59.8	103.9	0
NTZ (3,1)	362.1	59.8	103.9	0
NTZ (3,2)	369.1	57.0	103.0	0

Figure A5. NTZs with Hotspot in Patch (2,2) – Equilibrium Location Choices

0

5	0	1
0	*6*	0

Hotspot (2,2)

1

NTZ	3	1
1	*6*	0

Hotspot (2,2); NTZ (1,1)

0

5	0	1
NTZ	*6*	0

Hotspot (2,2); NTZ (1,2)

0

5	NTZ	1
0	*6*	0

Hotspot (2,2); NTZ (2,2)

0

4	4	1
2	*NTZ*	1

Hotspot (2,2); NTZ (2,1)

0

5	1	NTZ
0	*6*	0

Hotspot (2,2); NTZ (3,1)

0

5	0	1
0	*6*	NTZ

Hotspot (2,2); NTZ (3,2)

Table A5. NTZs with Hotspot in Patch (2,2) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
No policy	367.0	62.4	105.6	0
NTZ (1,1)	388.3	60.6	103.2	1
NTZ (1,2)	367.0	62.4	105.6	0
NTZ (2,1)	367.0	62.4	105.6	0
NTZ (2,2)	462.1	56.4	103.3	0
NTZ (3,1)	377.3	59.1	104.6	0
NTZ (3,2)	367.0	62.4	105.6	0

Figure A6. NTZs with Hotspot in Patch (3,1) – Equilibrium Location Choices

0

5	0	*4*
1	2	0

Hotspot (3,1)

1

NTZ	3	*4*
3	1	0

Hotspot (3,1); NTZ (1,1)

0

5	0	*4*
NTZ	3	0

Hotspot (3,1); NTZ (1,2)

0

5	NTZ	*4*
1	2	0

Hotspot (3,1); NTZ (2,1)

0

4	2	*4*
2	NTZ	0

Hotspot (3,1); NTZ (2,2)

1

4	4	*NTZ*
1	1	1

Hotspot (3,1); NTZ (3,1)

0

5	0	*4*
1	2	NTZ

Hotspot (3,1); NTZ (3,2)

Table A6. NTZs with Hotspot in Patch (3,1) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
No policy	370.9	65.8	107.4	0
NTZ (1,1)	387.5	63.9	105.0	1
NTZ (1,2)	371.6	65.6	106.6	0
NTZ (2,1)	370.9	65.8	107.4	0
NTZ (2,2)	377.8	62.8	105.7	0
NTZ (3,1)	476.7	53.1	104.2	1
NTZ (3,2)	370.9	65.8	107.4	0

Figure A7. NTZs with Hotspot in Patch (3,2) – Equilibrium Location Choices

0

4	3	0
1	0	*4*

Hotspot (3,2)

0

NTZ	5	0
3	0	*4*

Hotspot (3,2); NTZ (1,1)

0

5	3	0
NTZ	0	*4*

Hotspot (3,2); NTZ (1,2)

0

6	NTZ	0
1	1	*4*

Hotspot (3,2); NTZ (2,1)

0

4	3	0
1	NTZ	*4*

Hotspot (3,2); NTZ (2,2)

0

4	3	NTZ
1	0	*4*

Hotspot (3,2); NTZ (3,1)

0

5	3	1
1	2	*NTZ*

Hotspot (3,2); NTZ (3,2)

Table A7. NTZs with Hotspot in Patch (3,2) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
No policy	373.8	66.6	107.0	0
NTZ (1,1)	372.4	67.2	104.0	0
NTZ (1,2)	392.9	64.0	106.6	0
NTZ (2,1)	401.3	62.8	106.4	0
NTZ (2,2)	373.8	66.6	107.0	0
NTZ (3,1)	373.8	66.6	107.0	0
NTZ (3,2)	466.2	53.5	103.2	0

Figure A8. NTZs with Baseline Parameters – Equilibrium Location Choices

2

NTZ	5	1
3	1	0

No policy; NTZ (1,1)

0

6	2	1
NTZ	3	0

No policy; NTZ (1,2)

0

6	NTZ	2
1	3	0

No policy; NTZ (2,1)

0

4	4	1
2	NTZ	1

No policy; NTZ (2,2)

0

5	3	NTZ
1	2	1

No policy; NTZ (3,1)

0

5	3	1
1	2	NTZ

No policy; NTZ (3,2)

3

NTZ	5	1
NTZ	3	0

No policy; NTZ (col 1)

1

6	NTZ	2
2	NTZ	1

No policy; NTZ (col 2)

1

5	3	NTZ
1	2	NTZ

No policy; NTZ (col 3)

5

NTZ	NTZ	NTZ
3	3	1

No policy; NTZ (row 1)

1

6	4	1
NTZ	NTZ	NTZ

No policy; NTZ (row 2)

Table A8. NTZs with Baseline Parameters – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
NTZ (1,1)	364.9	52.7	102.7	0
NTZ (1,2)	374.5	52.1	102.8	0
NTZ (2,1)	368.1	53.7	102.5	0
NTZ (2,2)	361.1	53.8	102.0	0
NTZ (3,1)	365.1	52.9	102.4	0
NTZ (3,2)	364.9	52.7	102.7	0
NTZ (col 1)	424.6	46.1	101.9	3
NTZ (col 2)	397.2	49.3	102.7	1
NTZ (col 3)	386.4	48.4	103.3	1
NTZ (row 1)	456.2	39.4	102.3	5
NTZ (row 2)	414.7	43.7	102.1	1

Figure A9. NTZs with High Wage ($w = 1.35$) – Equilibrium Location Choices

1

5	2	1
1	2	0

High wage

4

NTZ	5	0
2	1	0

High wage; NTZ (1,1)

2

5	2	1
NTZ	2	0

High wage; NTZ (1,2)

1

7	NTZ	1
0	3	0

High wage; NTZ (2,1)

2

4	3	1
2	NTZ	0

High wage; NTZ (2,2)

2

4	3	NTZ
1	2	0

High wage; NTZ (3,1)

1

5	2	1
1	2	NTZ

High wage; NTZ (3,2)

5

NTZ	5	0
NTZ	2	0

High wage; NTZ (col 1)

2

6	NTZ	2
2	NTZ	0

High wage; NTZ (col 2)

2

4	3	NTZ
1	2	NTZ

High wage; NTZ (col 3)

Table A9. NTZs with High Wage ($w = 1.35$) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
No policy	383.9	51.3	110.4	1
NTZ (1,1)	431.7	45.4	111.6	4
NTZ (1,2)	402.0	49.1	111.5	2
NTZ (2,1)	408.8	48.1	110.5	1
NTZ (2,2)	401.6	47.5	110.6	2
NTZ (3,1)	398.8	47.8	110.6	2
NTZ (3,2)	383.9	51.3	110.4	1
NTZ (col 1)	463.0	39.0	110.7	5
NTZ (col 2)	425.8	43.5	109.7	2
NTZ (col 3)	398.8	47.8	110.6	2

Figure A10. NTZs with Low Wage ($w = 1.15$) – Equilibrium Location Choices

0

4	3	1
1	2	1

Low wage

1

NTZ	5	1
3	1	1

Low wage; NTZ (1,1)

0

5	3	1
NTZ	3	0

Low wage; NTZ (1,2)

0

6	NTZ	2
1	3	0

Low wage; NTZ (2,1)

0

4	4	1
2	NTZ	1

Low wage; NTZ (2,2)

0

4	4	NTZ
1	2	1

Low wage; NTZ (3,1)

0

5	3	1
1	2	NTZ

Low wage; NTZ (3,2)

2

NTZ	6	1
NTZ	3	0

Low wage; NTZ (col 1)

0

7	NTZ	2
2	NTZ	1

Low wage; NTZ (col 2)

0

4	4	NTZ
1	3	NTZ

Low wage; NTZ (col 3)

Table A10. NTZs with Low Wage ($w = 1.15$) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
No policy	338.0	56.6	96.4	0
NTZ (1,1)	360.2	56.2	96.0	1
NTZ (1,2)	359.8	53.1	96.1	0
NTZ (2,1)	358.6	54.2	96.8	0
NTZ (2,2)	351.3	54.3	96.2	0
NTZ (3,1)	350.6	54.0	95.9	0
NTZ (3,2)	355.3	53.1	96.7	0
NTZ (col 1)	410.7	47.6	94.5	2
NTZ (col 2)	386.2	50.0	95.9	0
NTZ (col 3)	359.8	50.9	94.6	0

Figure A11. NTZs with Zero Wage ($w = 0$) – Equilibrium Location Choices

0

2	2	2
2	2	2

Zero wage

0

4	4	4
NTZ	NTZ	NTZ

Zero wage; NTZ (row 2)

0

NTZ	5	1
3	1	2

Zero wage; NTZ (1,1)

0

3	2	2
NTZ	4	1

Zero wage; NTZ (1,2)

0

3	NTZ	3
1	4	1

Zero wage; NTZ (2,1)

0

1	4	1
3	NTZ	3

Zero wage; NTZ (2,2)

0

2	4	NTZ
2	1	3

Zero wage; NTZ (3,1)

0

2	2	3
1	4	NTZ

Zero wage; NTZ (3,2)

0

NTZ	5	1
NTZ	4	2

Zero wage; NTZ (col 1)

0

3	NTZ	3
3	NTZ	3

Zero wage; NTZ (col 2)

0

2	4	NTZ
1	5	NTZ

Zero wage; NTZ (col 3)

0

NTZ	NTZ	NTZ
4	5	3

Zero wage; NTZ (row 1)

Table A11. NTZs with Zero Wage ($w = 0$) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
No policy	224.0	55.8	55.8	0
NTZ (1,1)	261.8	57.9	57.9	0
NTZ (1,2)	249.2	56.5	56.5	0
NTZ (2,1)	244.6	57.3	57.3	0
NTZ (2,2)	244.8	57.4	57.4	0
NTZ (3,1)	243.7	55.4	55.4	0
NTZ (3,2)	243.6	56.0	56.0	0
NTZ (col 1)	302.1	53.1	53.1	0
NTZ (col 2)	275.5	56.7	56.7	0
NTZ (col 3)	276.2	50.7	50.7	0
NTZ (row 1)	334.3	49.0	49.0	0
NTZ (row 2)	312.3	48.7	48.7	0

Figure A12. Different Population Sizes – Equilibrium Location Choices

0

1	0	0
0	0	0

Population = 1

0

1	1	0
0	0	0

Population = 2

0

2	1	0
0	0	0

Population = 3

0

1	2	0
1	0	0

Population = 4

0

2	2	0
0	1	0

Population = 5

0

2	2	0
1	1	0

Population = 6

0

2	3	0
1	1	0

Population = 7

0

3	2	1
1	1	0

Population = 8

0

3	2	1
1	2	0

Population = 9

0

4	2	1
1	2	0

Population = 10

0

4	3	1
1	2	0

Population = 11

0

5	3	1
1	2	0

Population = 12

Table A12. Different Population Sizes – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
Population = 1	567.0	11.5	13.4	0
Population = 2	537.9	20.9	24.8	0
Population = 3	514.3	26.2	33.6	0
Population = 4	485.8	34.4	43.7	0
Population = 5	466.5	38.2	51.4	0
Population = 6	441.1	42.7	59.5	0
Population = 7	425.4	45.1	66.5	0
Population = 8	405.8	48.9	74.5	0
Population = 9	386.7	51.7	81.5	0
Population = 10	379.5	51.9	88.6	0
Population = 11	368.9	52.7	95.3	0
Population = 12	364.9	52.7	102.7	0

Figure A13. Different Population Sizes ($w = 1.35$) – Equilibrium Location Choices

0

1	0	0
0	0	0

High wage; Population = 1

0

1	1	0
0	0	0

High wage; Population = 2

0

2	1	0
0	0	0

High wage; Population = 3

0

1.5	1.5	0
0.5	0.5	0

High wage; Population = 4

0

2	2	0
1	0	0

High wage; Population = 5

0

2	2	0
1	1	0

High wage; Population = 6

0

3	2	0
1	1	0

High wage; Population = 7

0

3	3	0
1	1	0

High wage; Population = 8

0

4	3	0
1	1	0

High wage; Population = 9

0

4	2	1
1	2	0

High wage; Population = 10

0

5	2	1
1	2	0

High wage; Population = 11

1

5	2	1
1	2	0

High wage; Population = 12

Table A13. Different Population Sizes ($w = 1.35$) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
Population = 1	567.6	11.4	13.6	0
Population = 2	539.2	20.5	25.3	0
Population = 3	516.6	25.7	34.5	0
Population = 4	489.7	33.5	44.8	0
Population = 5	469.8	36.6	52.9	0
Population = 6	446.3	42.0	61.7	0
Population = 7	434.9	42.9	69.4	0
Population = 8	421.5	44.9	77.0	0
Population = 9	415.4	45.1	84.9	0
Population = 10	388.2	51.2	93.2	0
Population = 11	383.9	51.3	101.3	0
Population = 12	383.9	51.3	110.4	1

Figure A14. Different Population Sizes ($w = 1.15$) – Equilibrium Location Choices

0

1	0	0
0	0	0

Low wage; Population = 1

0

1	1	0
0	0	0

Low wage; Population = 2

0

2	1	0
0	0	0

Low wage; Population = 3

0

1.5	1.5	0
0.5	0.5	0

Low wage; Population = 4

0

2	2	0
0	1	0

Low wage; Population = 5

0

2	2	0
1	1	0

Low wage; Population = 6

0

2	2	1
1	1	0

Low wage; Population = 7

0

2	2	1
1	2	0

Low wage; Population = 8

0

3	2	1
1	2	0

Low wage; Population = 9

0

3	3	1
1	2	0

Low wage; Population = 10

0

4	3	1
1	2	0

Low wage; Population = 11

0

4	3	1
1	2	1

Low wage; Population = 12

Table A14. Different Population Sizes ($w = 1.15$) – Equilibrium Outcomes

Scenario	Stock	Fish yield	Total income	# of non-fishers
Population = 1	566.4	11.7	13.2	0
Population = 2	536.7	21.2	24.4	0
Population = 3	512.3	26.6	32.7	0
Population = 4	483.8	34.7	42.5	0
Population = 5	462.7	38.8	49.8	0
Population = 6	436.0	43.4	57.4	0
Population = 7	412.0	48.9	65.2	0
Population = 8	391.4	51.9	71.6	0
Population = 9	378.6	52.4	77.7	0
Population = 10	366.2	53.3	83.6	0
Population = 11	359.6	53.2	90.0	0
Population = 12	338.0	56.6	96.4	0