The Australian Journal of
Agricultural and
Resource Economics

Journal of the Australian
Agricultural and Resource
Economics Society

The Australian Journal of Agricultural and Resource Economics, 54, pp. 321–341

Marine protected areas in spatial property-rights fisheries*

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Marine protected areas (MPAs) and spatial property rights (TURFs) are two seemingly contradictory approaches advocated as solutions to common property failures in fisheries. MPAs limit harvest to certain areas, but may enhance profits outside via spillover. TURFs incentivize local stewardship but may be plagued by spatial externalities when the TURF size is insufficient to capture all dispersal. Within a numerical model parameterized to a California marine species, we explore the economic and ecological effects of imposing MPAs on a TURF-regulated fishery. Whether MPAs can enhance or diminish profits (or fish abundance) hinges critically on the level of coordination already occurring between TURF owners. If coordination is complete, private MPAs may already emerge in some TURFs; implementing additional MPAs reduces profits. However, to the extent that coordination is incomplete, strategically sited MPAs may be an effective complement to spatial property rights-based fisheries, increasing both fishery profits and abundance.

Key words: fisheries, marine protected areas, property rights, spatial bioeconomics, Territorial User Rights Fisheries (TURFs).

1. Introduction

The collapse of many of the world's fisheries (Jackson *et al.* 2001; Myers and Worm 2003; Worm *et al.* 2006) has led to the search for policy approaches to prevent further collapse and, perhaps, recover depleted stocks (Worm *et al.* 2009). The failure of many 'traditional' regulation structures to halt this collapse has led economists to propose several property rights-based approaches including Individual Fishing Quotas (IFQs or ITQs), which allocate units of harvest, and Territorial User Rights Fisheries (TURFs), which allocate units of space to private firms, cooperatives, or fishermen.[1]

Economists argue that appropriate assignment of rights internalizes externalities and facilitates stewardship, leading to sustainability through a profit

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[*] We gratefully acknowledge Gary Libecap, Crow White, Satoshi Mitarai, James Watson, David Siegel, and Will White for helpful suggestions and biophysical parameterization, Ming Ng for map preparation, and The Paul G. Allen Family Foundation, NSF's Biocomplexity program, and Environmental Defense Fund for financial assistance.

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[1] For example, the 2007 reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act allows for various tradable property schemes.

doi: 10.1111/j.1467-8489.2010.00495.x

motive (Costello *et al.* 2008). With private property rights over tracts of ocean, owners have a strong incentive to manage their TURFs for long-term profitability, which typically involves steady-state solutions with sustainable harvests in perpetuity. However, local stewardship may be somewhat eroded when fish disperse from these spatially delineated patches (Janmaat 2005; Orensanz *et al.* 2005).

In contrast to these rights-based approaches, conservationists have called for the establishment of Marine Protected Areas (MPAs), arguing that if properly designed, spatial ocean closures create networks that sustain fish populations despite the management outside. Empirical evidence suggests that biomass does in fact increase within MPAs (Halpern 2003). Secondarily, it is sometimes argued that fish produced within the reserve will 'spillover' into the fished area, thus enhancing the overall fishery. This second claim has recently been substantiated in bioeconomic models (Janmaat 2005; Sanchirico *et al.* 2006; Costello and Polasky 2008). However, to the extent that private TURF owners steward local stocks, spatial property rights seem to obviate the need for MPAs.

We develop a metapopulation model where the populations are privately managed within adjacent TURFs. We ask: what is the effect of exogenously imposed MPAs on profits and conservation outcomes? In other words, if TURFs are implemented and enforced, does this remove the benefits of MPAs? Does MPA implementation always increase fish abundance at the cost of fisheries profits? The answers turn out to hinge on the level of coordination among TURF owners. Thus, whether spatial property rights and MPAs are complementary or contradictory will depend on the completeness of the incumbent property right. This qualitative finding may help guide policy on spatial management of marine resources.

Within the fisheries economics literature, a number of authors seek to determine the consequences of imposing MPAs on existing fisheries management regimes (prominent examples include Sanchirico and Wilen (2001, 2002) and Smith and Wilen (2003)).[2] In contrast to more naïve economic models of fisherman behaviour, these papers explicitly consider the economic behaviour of fishermen in response to MPA implementation. Of particular relevance to this research are Sanchirico and Wilen (2001, 2002) who respectively study imposition of marine reserves on a fishery regulated via limited effort or entry and an open-access fishery. Using a three-patch stylized model, Sanchirico and Wilen (2002) find that under special circumstances, a 'win–win' is possible, where profits (measured by lease prices) can increase following the exogenous imposition of a reserve. Sanchirico and Wilen (2001) also find similar results (potential increase in harvest) in a two-patch open-access model, though again, only under certain specific conditions. In a numerical model parameterized to a sea urchin fishery, Smith and Wilen

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[2] Though far from an exhaustive list, these papers pay particular attention to *spatial* responses by fishermen to closures, and thus are most relevant for our study.

(2003) find that after accounting for spatial economic behaviour in response to a patch closure, exogenously imposed MPAs unambiguously decrease harvest; the theoretical possibility of increased harvest did not obtain in a realistic setting. Our paper primarily differs from these papers by modeling status quo management as a spatial property rights (rather than open-access or limited entry) system. A related literature investigates MPAs in a spatially optimized fishery. When harvest is optimized across space, there are certain conditions under which MPAs emerge as being economically optimal (Janmaat 2005; Sanchirico *et al*. 2006; Costello and Polasky 2008).[3]

The model developed in this paper considers the imposition of MPAs on an existing TURF system. We numerically apply this model to a stylized species, similar to kelp bass, using oceanographic and ecological data from the southern California coast. We find the following results: (i) fully coordinated TURFs can include private MPAs, even without government intervention; (ii) imposing additional MPAs decreases system-wide profits under full coordination; (iii) abundance will typically (but not always) increase under exogenous MPA placement in both coordinated and uncoordinated TURF fisheries; (iv) profits can increase with imposed MPAs in the absence of coordination; and (v) 'optimal' MPA networks in uncoordinated TURF fisheries may be larger than 'optimal' MPA networks in coordinated TURF fisheries. The last two results stand in contrast to Smith and Wilen (2003) who find that, after accounting for the spatial behaviour of fishermen, imposed MPAs lead (in 100 per cent of cases) to a decrease in fishery profits. We find that exogenously imposed MPAs can increase profits in 81 per cent of cases, provided the existing TURF owners behave non-cooperatively.

2. Model and methods

Here, we develop a spatial bioeconomic metapopulation model with a total of N heterogeneous TURFs. The biological and economic environment is homogeneous intra-TURF, and each TURF is owned and managed by a single entity without government intervention.

The inter-TURF metapopulation model builds on Costello and Polasky (2008), Sanchirico and Wilen (1999), and others. Postharvest (i.e. escaping) adults, Y_{it} each have fecundity, f, and a fraction D_{ij} of larvae produced

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[3] The model developed here shares some structural similarities with both Costello and Polasky (2008) and Janmaat (2005). However, some key distinctions are worth highlighting in more detail. First, while Costello and Polasky (2008) consider a spatial metapopulation model and find that MPAs emerge as optimal, they only consider a profit-maximizing sole owner. They also consider how harvest and escapement in patches outside an MPA may change in response to an imposed MPA but do not consider the impact of imposed MPAs on total abundance. Janmaat (2005) develops a two-patch TURF model, comparing outcomes in the absence of coordination with those under a profit-maximizing sole owner (effectively a coordinated TURF fishery). He finds that the absence of coordination leads to suboptimal outcomes that depend on spatial connectivity, and also that the profit-maximizing sole owner solution may include MPAs. However, he does not look at exogenously imposed MPAs in a TURF fishery.

disperse from TURF i to TURF j. Settlement success depends linearly on the amount of suitable habitat, K_i in the TURF. Thus, settlement to TURF j is given by:

$$S_{jt+1} = K_j \sum_{i=1}^{N} D_{ij} f Y_{it} \tag{1}$$

Settlers exhibit density-dependent survival to adulthood. Thus, the number of recruits is given by:

$$R_{jt+1} = F(S_{jt+1}) \tag{2}$$

where $F'(S) > 0$ and $F''(S) < 0$. Finally, escaping adults may exhibit density-dependent survival, given by $G(Y)$, though adults do not disperse out-of-TURF.[4] Combining new recruits and surviving adults, and expressing in terms of the patch-specific mortality rate, M_{it} (where $Y_{it} = (1 - M_{it})X_{it}$), we get the main state equation describing preharvest adults:

$$X_{jt+1} = R_{jt+1} + G\big((1 - M_{jt})X_{jt}\big) \tag{3}$$

$$= F\left(K_j \sum_{i=1}^{N} D_{ij} f (1 - M_{it}) X_{it}\right) + G\big((1 - M_{jt})X_{jt}\big) \tag{4}$$

In the absence of coordination, each TURF owner chooses a mortality rate M_i to maximize steady-state harvest, $M_i X_i$.[5]

An important feature of this metapopulation is that TURF owner i's choice of mortality rate may depend on the mortality rate chosen in all connected TURFs. Thus, this is an N person game whereby each owner maximizes steady-state harvest, taking as given the mortality rate in all other TURFs. Following Heintzelman *et al.* (2009) we later extend this model to allow for full coordination across TURF owners. We model coordination using a simple profit-sharing mechanism whereby all profits are pooled and distributed pro rata ($1/N$) to each TURF owner.[6] Profit sharing incentivizes TURF owners to coordinate harvest because an increase in profit in a single TURF spills over to affect profits in other TURFs.[7]

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[4] Our empirical model includes TURFs of a typical size of 210 square kilometres, which is more than an order of magnitude larger than the home range of many marine species (see, e.g. White and Costello 2010).

[5] Here, TURF profit is proportional to harvest, so marginal harvest cost is constant. Including a stock effect does not change our qualitative results, as illustrated in Section 4.4.

[6] In the initial analysis, participation in the full profit-sharing mechanism is mandatory. This assumption is relaxed in additional analysis, where participation is endogenized.

[7] Uchida (2007) considers the use of profit sharing by co-op members within a TURF as a means of resolving the common pool problem.

Even the relatively simple dynamics expressed in Equation 4 do not yield a closed form analytical expression; however, a special case is amenable to analytical manipulations. Setting $D_{ii} = 1$, $D_{ij} = 0$ (for $i \neq j$), $G(Y) = \alpha Y$, and using the Beverton–Holt functional form for $F(S)$ (see Equation 7) delivers an analytical expression for the optimal mortality rate in patch i in the absence of dispersal:

$$M_i^* = 1 - \frac{1}{\alpha + \sqrt{(1-\alpha)b_0 f K_i}} \tag{5}$$

Here, higher habitat (K_i) fecundity (f), and recruitment rate b_0 all lead to increased optimized mortality. More nuanced interpretations of the parameters' effects on solutions emerge when we consider more complicated (and realistic) versions of this model.

3. Numerical application

We apply the general version of this model to a stylized nearshore marine species in Southern California. For concreteness, the life-history biological parameters are based on kelp bass (*paralabrax clathratus*), an abundant species of primarily recreational fishing importance, with an association with kelp in our study region. The area under consideration stretches from north of Morro Bay on the Central Coast of California south to Santa Monica Bay, and includes the major Channel Islands (Figure 1). This region has been divided into $N = 48$ separate (hypothetical) TURFs with an average size of 210 km^2. Figure 1 contains a map of these hypothetical TURFs.

3.1. Parameterization of the biological model

The biological model for this stylized species is loosely based on the ecological model in White and Caselle (2008) and also corresponds with the parameterization contained in the Marine Life Protection Act (2009). Fecundity of escaping adults is $f = 30.4$ after correcting for losses to ocean advection. The larvae produced by escaping adults is then apportioned via the dispersal kernel, a 48×48 matrix, D, where element D_{ij} represents the proportion of larvae originating in TURF i that disperse to TURF j. This kernel was produced using oceanographic vector fields and a pelagic larval duration (PLD) of 30–31 days (Oda *et al.* 1993; Cordes and Allen 1997).[8] Larval dispersal kernels were calculated following procedures outlined in Mitarai *et al.* (2009) and Watson *et al.* (2009). Any given element, D_{ij} is quantified as the probability that a water molecule originating at a source site (i) will arrive at a destination site (j) at the end of the PLD. This calculation of the site-to-destination probabilities defines the potential larval dispersal (Watson *et al.*

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[8] The PLD provides a measure of the date at which the larvae can settle, provided it locates suitable habitat.

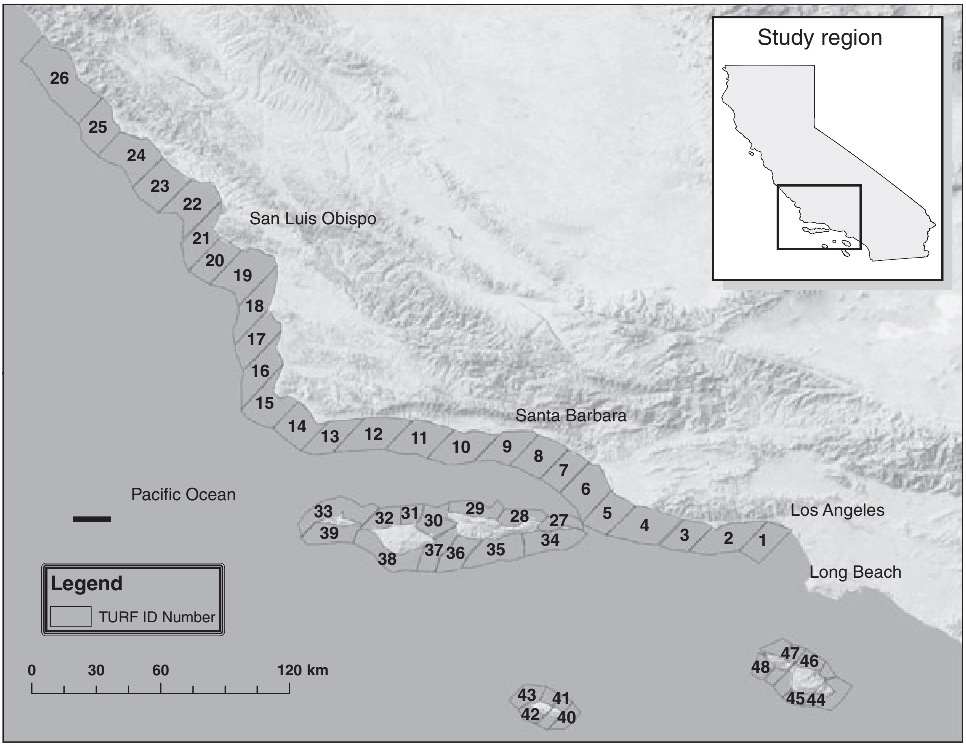

Figure 1 Southern California Coast with 48 hypothetical TURFs.

2010). Based on satellite imagery, kelp cover percentage $0 \leq c_i \leq 1$ in each TURF is used as proxy for habitat K_i, such that:

$$K_i = 209.5 * c_i + 0.55 \tag{6}$$

Settlement, defined by Equation 1, is scaled by 0.144 to capture larvae survivability. These settlers experience density-dependent recruitment to adulthood according to the Beverton–Holt equation:

$$F(S) = \frac{b_0 * S}{1 + \frac{b_0 * S}{b_1}} \tag{7}$$

where $b_0 = 0.6305$ and $b_1 = 0.0387$.

Adults escaping harvest also experience density-dependent survival according to the exponential equation:

$$G(Y) = a_0 * Y^{a_1} \tag{8}$$

where $a_0 = 0.3918$ and $a_1 = 0.8638$.[9]

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[9] The parameterization captured in Equations 6–8 is derived from the literature cited above and is a result of the 'Flow, Fish, and Fishing' biocomplexity working group at the University of California, Santa Barbara.

3.2. Methodology

Given the above parameterization, for a given vector of mortalities $\mathbf{M}$, the steady-state number of preharvest adults $\mathbf{X}^{\star}$ can be determined. To find the Nash Equilibrium vector of mortalities, an initial vector of steady-state mortalities is posited. Taking other TURFs' steady-state mortalities $M^{\star}_{j \neq i}$ as given, each TURF owner i chooses a steady-state mortality level $M^{\star}_{i}$ to maximize steady-state harvest.[10] Fixed-point iteration is used on the resulting vector of mortalities until the mortality choice by each TURF owner constitutes a best-response to the mortality choice by all other patch owners.[11]

4. Results

Our focus is on the economic (i.e. profit) and ecological (i.e. abundance) effects of imposing individual MPAs on an existing TURF system. Because dispersal and habitat are heterogeneous inter-TURF, the consequences of MPA implementation will depend on the location in which it is sited. We thus examine the effects of MPA implementation in each of the 48 TURFs. We conduct this analysis under three assumptions about property rights coordination outside: (i) uncoordinated TURF owners (Subsection 1), (ii) perfectly coordinated TURF owners (Subsection 2), and (iii) owners who self-select into a cooperative arrangement (Subsection 5). Subsections 3 and 4 analyze alternative closure strategies and model sensitivity.

4.1. Implementing an MPA in an uncoordinated TURF system

We initially consider a TURF system with no coordinating mechanism between TURF owners. Here, each TURF owner maximizes private return taking decisions of other TURF owners as given. The ensuing Nash Equilibrium is inefficient in the sense that each TURF owner i has a private incentive to over-harvest her own TURF (provided $D_{ij} > 0$ for some j). When choosing an optimal harvest, a TURF owner ignores the dispersal of larvae from her TURF into other spatially connected TURFs, which leads to a system-wide inefficiency.

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[10] In the absence of coordination, each TURF owner simply maximizes his own return, while in the case of full coordination, each TURF owner maximizes his $1/N$ share of total returns across all TURFs.

[11] Extensive perturbation analysis was conducted to ensure that the equilibrium found through the fixed-point iteration was unique.

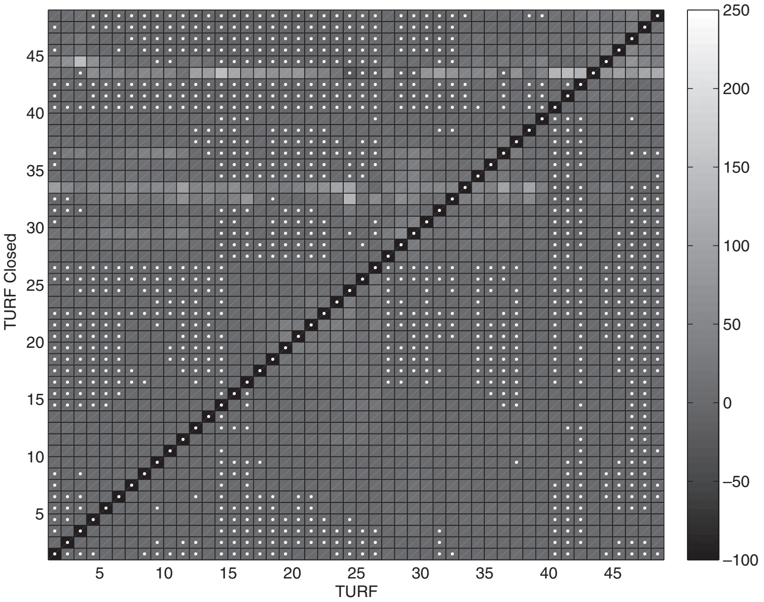

Figure 2 Element (*i*,*j*) is the percentage change in profit in TURF *j* arising from a forced closure of TURF *i*, in the absence of coordination among TURF owners. Cells with profit losses are indicated by a white dot.

First, consider the effects on TURF-specific profits of imposing an MPA.[12] The shading in Figure 2 represents the percentage change in profits in TURF *j* (horizontal axis) because of a closure of TURF *i* (vertical axis). Lighter pixels indicate increases in TURF-specific profits, whereas darker pixels indicate decreases in profits (a white dot also indicates TURFs with profit losses). Imposing a closure on TURF *j* may increase spillover of larvae to adjacent fished TURFs, thus increasing profits in TURF *i*. From Figure 2, TURFs connected (via dispersal) to closed areas often benefit from closures. However, the closed TURF loses 100% of its profits, creating the dark diagonal band of pixels.

Thus, while connected TURFs typically benefit from an imposed MPA, their gain must be compared against the loss of profit resulting from the closure. Figure 3 shows the percentage change in total fishery profit (vertical axis) because of an imposed closure of TURF *i* (horizontal axis). Arbitrarily placed MPAs typically increase system-wide profits, with an increase in profits occurring in 81 per cent of cases. In stark contrast, Smith and Wilen (2003) find in 100 per cent of cases, that imposing MPAs on a limited-entry fishery

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[12] For our purposes, we abstract from the precise mechanism by which this imposed closure occurs. The MPA could be created at the same time as the TURF system, the TURF owner could be bought out by regulatory agencies, or the TURF owner may simply be forced to forgo harvest. In practice, if TURF owners fear they may be forced to relinquish tenure of their TURF, this may influence their harvest decisions (e.g. Costello and Kaffine 2008). Such considerations are beyond the scope of this paper.

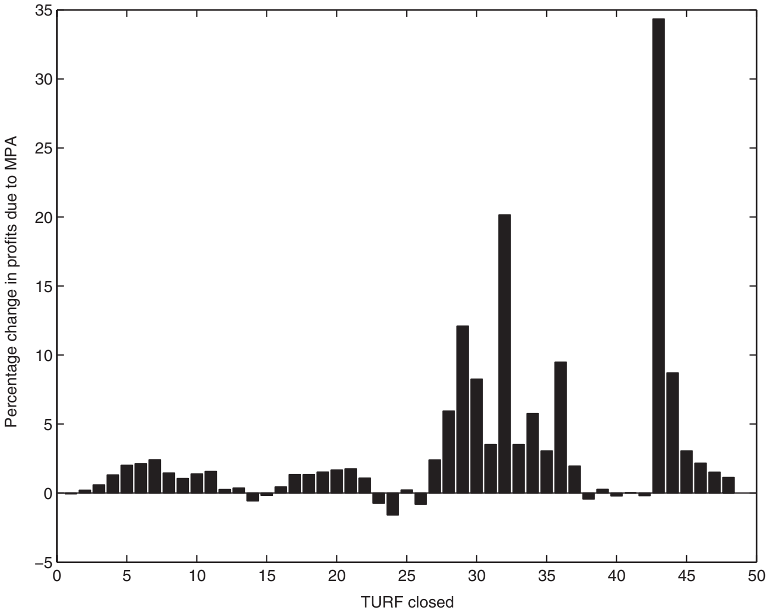

Figure 3 Percentage change in system-wide profit from a forced closure of each TURF, with no coordination.

leads to a decrease in total fishery profits because of the spatial behaviour of fishermen. This suggests that while uncoordinated TURFS suffer from a spatial externality (Janmaat 2005), property right security allows each TURF owner to capture enough spillover benefits of closure to often offset the loss of harvest within the MPA.

We have demonstrated that profits in uncoordinated TURFs may increase under an imposed MPA. What are the associated consequences on fish abundance? In Figure 4, changes in abundance (vertical axis) are displayed because of an imposed closure of TURF *i* (horizontal axis). For all but one case, total abundance increases under an imposed closure. Furthermore, imposed MPAs on uncoordinated TURFs lead to a 'win–win' increase in profits and abundance in a majority of cases. For example, closing TURF 43 leads to a 34 per cent increase in system-wide profit and a 28 per cent increase in system-wide fish abundance. Thus, even though there is more harvest in aggregate as a result of the closure, escapements have sufficiently increased to lead to a net increase in total abundance.

The intuition for this striking result is as follows: suppose TURF *i* is closed, and consider the effect on harvest in TURF *j* that is supplied larvae from TURF *i*. TURF *j* will decrease escapement, because of crowding out from incoming larvae on locally produced larvae. This reduction in escapement tends to decrease adult abundance in TURF *j*. Two countervailing effects occur: First, TURF *i* (the closed patch) will itself increase in abundance (as a result of the closure). Second, the response of patch *j* (to the closure of patch *i*) may cause TURFs supplied *by* TURF *j* to increase in abundance through

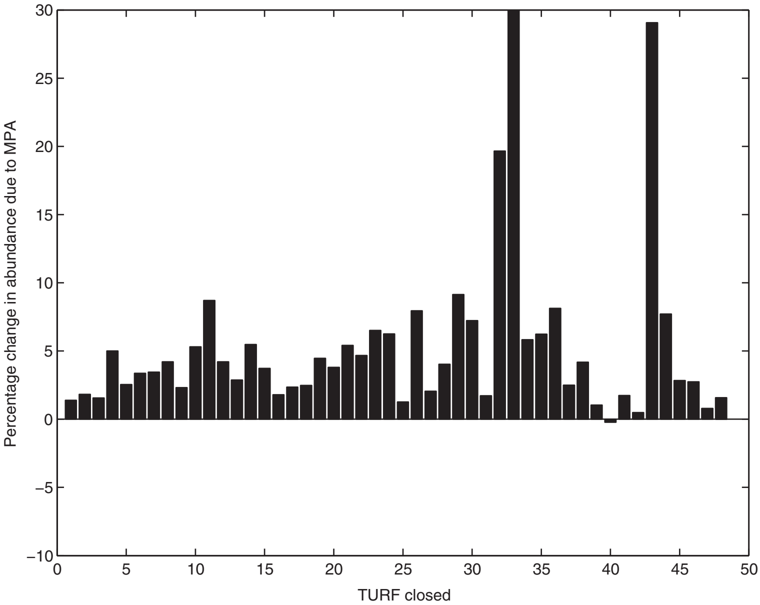

Figure 4 Percentage change in system-wide abundance from a forced closure of each TURF, with no coordination.

the same logic as above (though applied in reverse). Loosely speaking, when the closed TURF is a 'sink' (i.e. it does not supply larvae to other TURFs), system-wide biomass can only increase as a result of the closure. But when the closed TURF is a 'source' (i.e. it supplies larvae to other TURFs) system-wide biomass may either increase or decrease. In the example presented here, no TURFs are pure sinks or pure sources, and we find that abundance typically increases.

4.2. Implementing MPAs on a fully coordinated TURF system

We have shown that when TURF owners are uncoordinated, exogenously imposed MPAs may (but do not necessarily) simultaneously increase profits and fish abundance. We now consider a fully coordinated TURF system in which profits are shared among TURF owners.[13] How does full coordination change behaviour of TURF owners under an imposed MPA? Intuitively, under full coordination, many TURF owners will reduce fishing pressure, as a TURF owner now receives benefit from larval production in his patch via spillover and subsequent harvest in adjacent patches.[14] In some cases, the

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[13] Though not formally proven here, under a full profit-sharing coordinating mechanism, first-best harvest rules are obtained. Intuitively, the objective of each TURF owner under a full profit sharing is to maximize total fishery profits, which is precisely the objective of a sole-owner.

[14] Empirical observations of coordination among TURF owners in Japan is documented in Uchida (2007) and Yamamoto (1995).

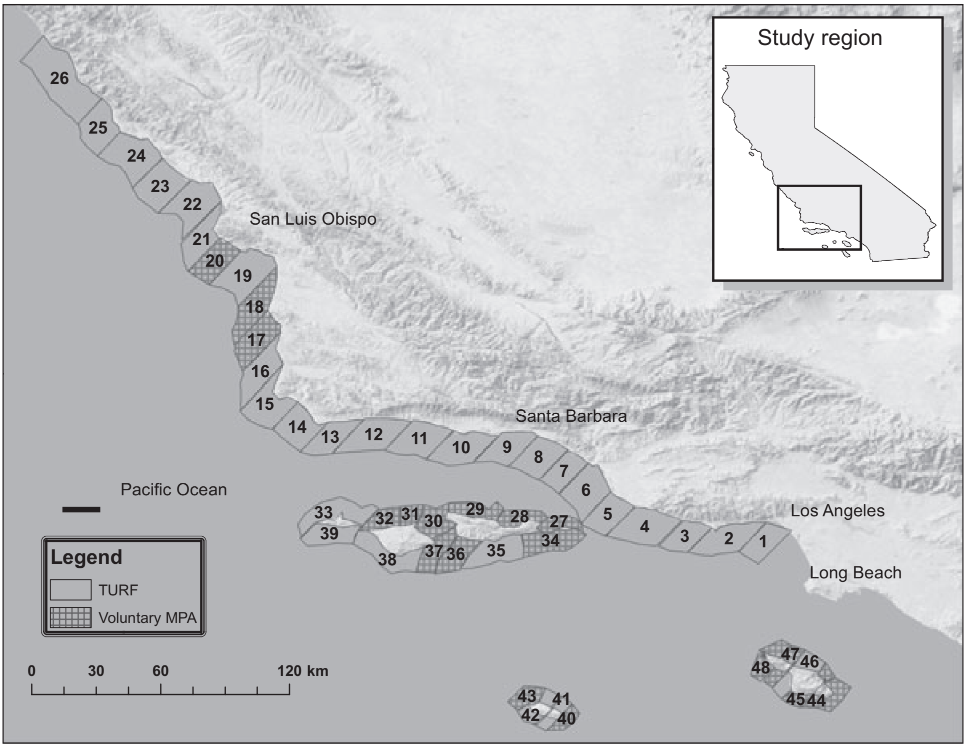

Figure 5 Southern California Coast with 48 hypothetical TURFs and voluntary MPAs under full coordination in crosshatch.

reduction causes optimal fishing pressure to go to zero, and in effect, a TURF owner voluntarily creates a private MPA (see crosshatched TURFs in Figure 5).[15] This occurs when their profit share from a system in which their TURF is closed to fishing exceeds their profit share from a system in which they harvest something out of their TURF. In our study system, 37.5 per cent of TURF owners find it privately optimal (under profit sharing) to close their TURFs to harvest.[16]

Thus, under full coordination, there may be a private incentive to cease harvest in particular TURFs. In such cases, what are the effects of imposing *additional* MPAs? Because each TURF owner receives the same profit, comparisons of total fishery profit will also reveal the effects on TURF-specific profits. The percentage change in total fishery profit (vertical axis) due to an imposed closure of TURF *i* (horizontal axis) is presented in Figure 6. Intuitively, total profits (and thus all TURF owners' profits) are (weakly) reduced

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[15] That MPAs emerge as an optimal spatial harvest strategy is consistent with the sole-owner results found in Costello and Polasky (2008), Sanchirico *et al.* (2006) and Janmaat (2005).

[16] Voluntary private closures have been documented in many real-world TURF-managed fisheries (e.g. in Chile, New Zealand, and the Philippines).

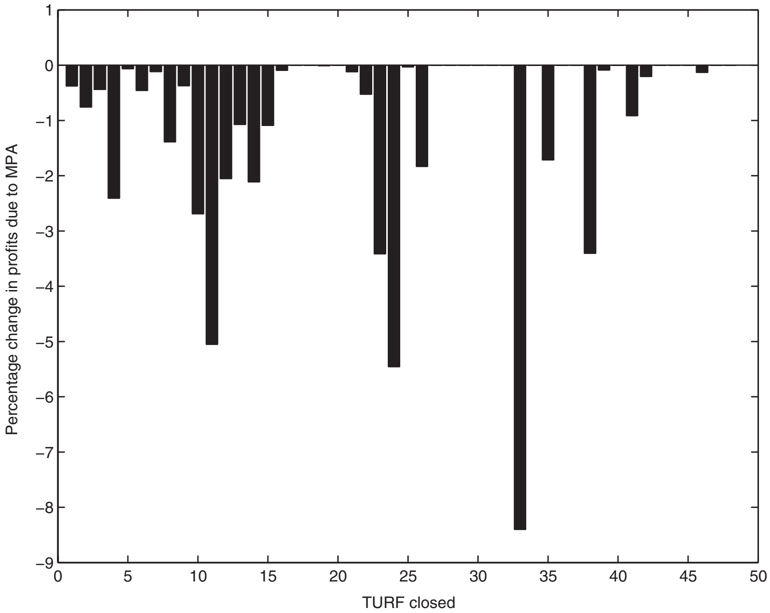

Figure 6 Percentage change in system-wide profit from a forced closure of each TURF, with full coordination.

by imposing additional closures. Because profitable MPAs are already privately implemented by the fully cooperative TURF owners, additional closures reduce system-wide and TURF-specific profits, by definition. Thus, at best, imposed closures are redundant under fully coordinated TURFs leading to no change in total fishery profits (specifically, when the imposed closure occurs in a TURF that would have been privately closed). At worst, additional MPAs above and beyond the private closures reduce total fishery profits, though the reductions are modest (up to 8.5 per cent) in our study area.

Thus, there is no clear economic rationale for additional closures in a fully coordinated TURF fishery, provided fishery profit is the sole objective. However, it is worth considering the impact of imposed MPAs on fish abundance. In Figure 7, changes in fish abundance (vertical axis) are displayed because of an imposed closure of TURF *i* (horizontal axis). In general, total abundance increases or maintains; however in one case, abundance decreases. Thus, while additional closures in a fully coordinated fishery can result in the conventional trade-off between profits and abundance, in some cases additional closures can actually result in a 'lose–lose' decrease in profits and abundance.

Consider the intuition behind this result. When a closure occurs, abundance in the closed TURF always increases. But for two reasons, abundance in other TURFs may decrease in response to the closure, leaving the net effect on abundance ambiguous. First, suppose the closed TURF *i* is a sink, so it sends little or no larvae to other TURFs but receives larvae from other TURFs. Consider the consequence on a connected TURF *j*. When TURF *i*

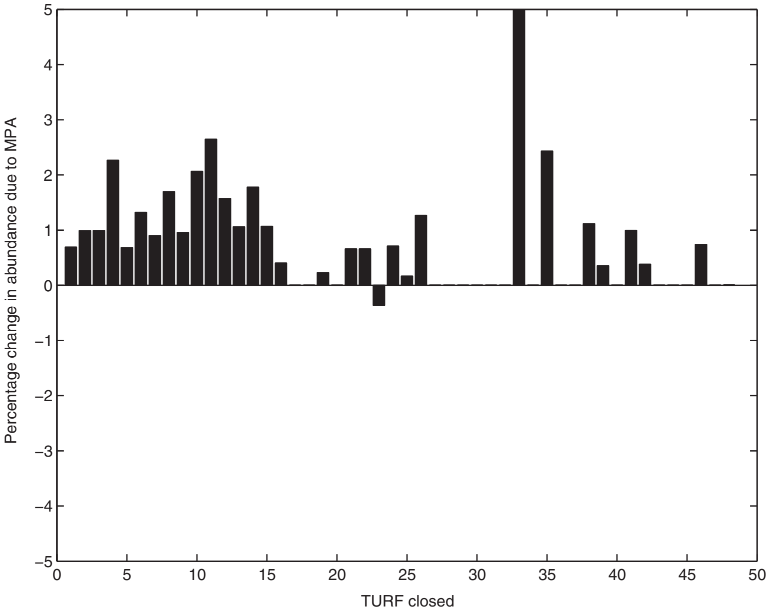

Figure 7 Percentage change in system-wide abundance from a forced closure of each TURF, with full coordination.

was fished, TURF owners received some profit from harvest occurring in *i*. This in turn created an incentive for reasonably high escapement in TURF *j* to supply TURF *i* with larvae. But when TURF *i* is closed, the incentive for escapement in TURF *j* is diminished. This reasoning is consistent with Proposition 5 in Costello and Polasky (2008) where suboptimal area closures lead the sole owner to decrease escapement (increase harvest) in connected areas. Second, suppose the closed TURF is a source, which supplies larvae to TURF *j*. In that case, the larval supply to TURF *j* is enhanced by the closure. Because of density dependence, there is a crowding out between these incoming larvae and larvae locally produced by escaping adults in TURF *j*. Again, this provides an incentive to decrease escapement in TURF *j*. The net effect is an empirical question, and we find evidence that it can go in either direction, depending on which TURF is closed.

4.3. Alternative MPA strategies in uncoordinated fisheries

We have shown that a completely uncoordinated TURF fishery is likely to over-harvest and that reserves may be able to enhance both profits and abundance of the entire system. On the other hand, fully coordinated TURF owners will determine the optimal TURFs to close, and will coordinate on harvest in the remaining open patches. In our numerical example, the uncoordinated TURF fishery has an economic value of just 28 per cent of that attainable under full cooperation (with the associated network of 18 MPAs).

To test the effects of implementing reserves on an uncoordinated TURF fishery, in Section 4.1 we imposed single-TURF reserves and found that they could increase profits by as much as 34 per cent. Whether larger networks of MPAs could increase profits even further in an uncoordinated TURF fishery is the focus of this subsection.

To examine this question we conduct two experiments. First, we examine the effects of imposing the 18-TURF MPA network that is optimal under a coordinated fishery on the uncoordinated TURF fishery. It turns out that this network improves profits substantially, from 28 per cent of the coordinated profits (circle in Figure 8) to 95 per cent of the coordinated profits (diamond in Figure 8). But because the fishery dynamics differ substantially between coordinated and uncoordinated TURF owners, the optimal reserve network in a coordinated TURF fishery may differ from that in an uncoordinated TURF fishery. Our second experiment was to accumulate a network of MPAs by closing, in turn, the TURF that had the largest marginal impact on system-wide profits in an uncoordinated TURF fishery (see curve in Figure 8). We continued this accumulation until adding an additional TURF to the reserve network decreased system-wide profits. Using this method (known as a 'greedy' algorithm in operations research) resulted in an MPA network that contained 25 TURFs, yielding 98 per cent of the profits (square

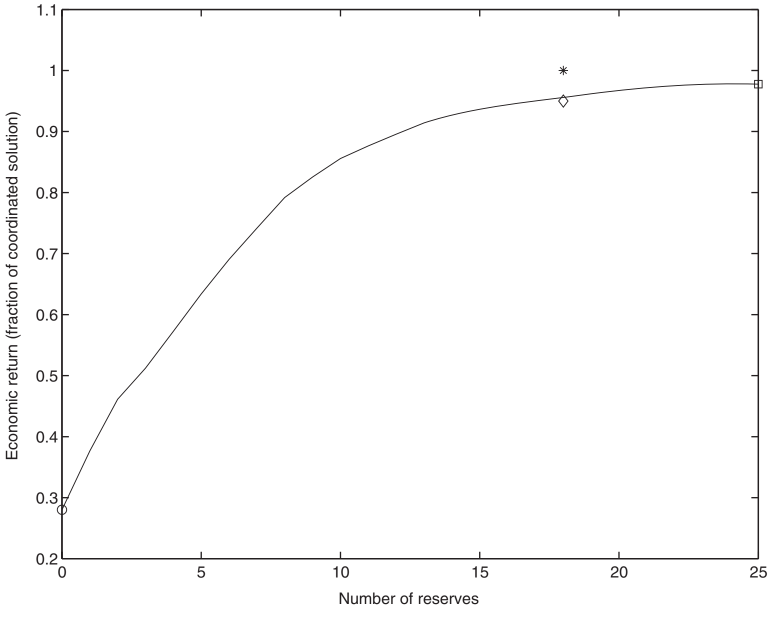

Figure 8 System-wide profit in uncoordinated system as a function of number of reserves, given that they are optimally placed. Profits are expressed as a fraction of optimized profits in the coordinated system. Also shown are: profits in uncoordinated system without reserves (circle), profits in uncoordinated system with optimized reserves (square), profits in uncoordinated system with reserve network that is optimal under coordinated system (diamond), and optimized profits under a coordinated fishery (asterisk).

in Figure 8) that are attainable under the fully coordinated fishery (asterisk in Figure 8). This result is particularly striking for two reasons. First, that an optimally designed MPA network could increase profits from just 28 per cent (of coordinated profits) to 98 per cent is an important policy finding. Second, that the optimal MPA network in an uncoordinated TURF fishery may be quite large (over half of the TURFs are optimally closed in this example), and substantially larger than the optimal coordinated network (25 vs 18 MPAs), could help inform MPA network design adjacent to TURF-managed fisheries.

4.4. Comparative statics and model sensitivity

Our results suggest that MPAs overlayed on a TURF-regulated fishery may improve both economic and ecological performance. But these results derive from a model with specific parameter values tuned to species in California. In this subsection, we begin by briefly examining the characteristics that tend to make a patch a beneficial candidate for closure. We use two methods to conduct these comparative statics. First, we develop a two-patch version of the model described in Section 2.[17] By varying kelp (K_1), self-recruitment (D_{11}), out-dispersal (D_{12}), and in-dispersal (D_{21}), we can explore the effects of closing patch 1 on abundance and profits of the system. Second, we use our results presented in Sections 1 and 2 and regress the outcome of interest (either abundance or profits) against the variables of the additionally closed patch. Each of these methods allows us to explore the consequences of imposing an MPA with different patch-specific features on system abundance and profits.

The tables are organized as follows: Table 1 refers to the uncoordinated TURF fishery and Table 2 refers to the fully coordinated TURF fishery. The first column defines the variable that is being changed in the additionally closed patch. The second column gives the consequences of that closure on profits, using the two-patch model. The third column gives the consequences

Table 1 Effect of closed patch features on system profits and abundance in uncoordinated fishery

Variable	Uncoordinated fishery			
	Profit		Abundance	
	2-patch	Regression	2-patch	Regression
Kelp	+	+	+	+
Self-Recruitment	+	+	+	–
Out-Dispersal	+	+	+/–	?
In-Dispersal	0	?	0	+

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[17] We use the base case $D_{ij} = 0.5$, for $i = \{1,2\}$ and $j = \{1,2\}$; and $K_1 = K_2 = 1$.

Table 2 Effect of closed patch features on system profits and abundance in coordinated fishery

Variable	Coordinated fishery			
	Profit		Abundance	
	2-patch	Regression	2-patch	Regression
Kelp	−	−	+	+
Self-Recruitment	+/−	+	+	?
Out-Dispersal	+	?	−/0	?
In-Dispersal	0/−	−	−	+

of that additional closure on profits, using the regression approach. The fourth column gives the consequences of that closure on abundance, using the two-patch model. The fifth column gives the consequences of that closure on abundance, using the regression approach. The entries are interpreted as follows: a '+' suggests that patches with higher levels of that variable tend to increase the respective performance metric (abundance or profit), given the institutional structure (uncoordinated or coordinated TURF). A '–' suggests the opposite. A '0' or '?' means that the result was either insensitive or not statistically different from zero.

There is general agreement between the two-patch model and the regression approach, although one would not necessarily expect full concordance. For one thing, parameters are to some extent correlated in the regression approach as it was based on the empirical example, so it is difficult to know precisely what is driving the result. Perhaps more importantly, the regression approach examines the consequences of *additional* closures. So, for example, when evaluating the effects of an additional closure on profits in a coordinated system, one would expect the typical result to be negative (because in that case the optimal reserve network would already have been privately implemented). The main discrepancies between the two-patch and regression approaches exist in the prediction of the effects of D_{11} on abundance (in the uncoordinated model) and the prediction of D_{21} on abundance (in the coordinated model). In an uncoordinated TURF fishery, patches with better habitat and self-recruitment tend to make better reserves (to increase both profits and abundance). Patches with higher out-dispersal tend to make better reserves for profits, but may not affect abundance, and the effects of in-dispersal are relatively small. In a fully coordinated TURF fishery, closing additional patches with better habitat tends to increase abundance but decrease profits. Closing patches with higher self-recruitment tends to increase both profits and abundance, while the effects of other dispersal characteristics are more ambiguous.

The tables above show that we can make some systematic predictions about the features of patches that make 'good' additional reserves in a TURF-managed fishery. In our analysis the fully coordinated TURF fishery

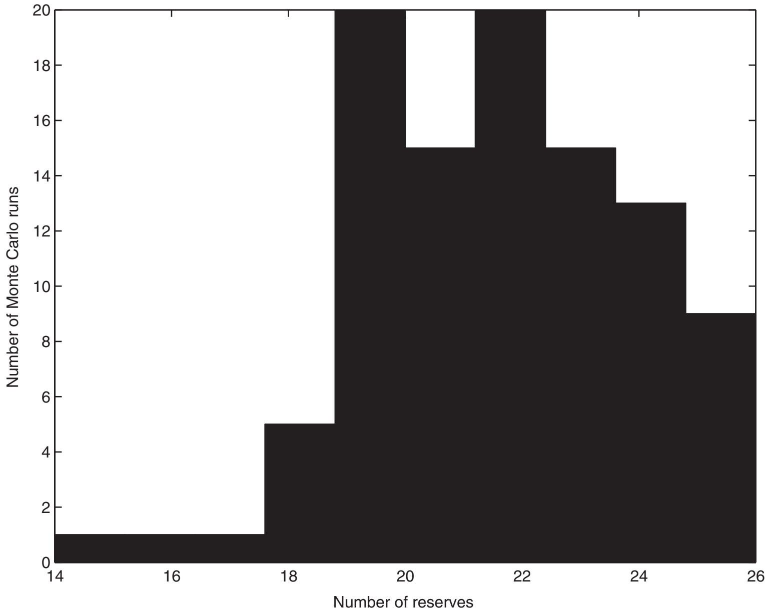

Figure 9 Histogram of number of TURFs optimally closed in a fully coordinated TURF fishery for the Monte Carlo sensitivity analysis.

contained 18 privately implemented reserves. To explore whether this result was an artifact of our specific spatial pattern of habitat, dispersal, and TURF size, we conducted a Monte Carlo sensitivity analysis. We randomized K_j, D_{ij}, and patch area,[18] and determined the number of TURFs optimally closed for reserves in the fully coordinated system. We repeated this experiment 100 times; the histogram of optimal TURFs closed is given in Figure 9. The number of TURFs optimally placed in reserves ranged from 14 to 26 with a mean of 22, suggesting that: (i) our result that reserves may increase profit is not sensitive to parameter values (at least within the context of our experiment) and (ii) our base case, which yielded 18 reserves, may have (in some sense) been conservative, in that most parameterizations yielded more TURFs in reserve.

A final feature of our model that deserves further exploration is our specification of costs. In our base model, we assume that costs are linear in harvest, so marginal cost is constant. In many fisheries a more realistic treatment would be to allow marginal harvest costs to increase as the density of stock in a patch is drawn down within a period. This so-called ‘stock effect’ is prominent in many bioeconomic models; while it is difficult to predict the quantitative consequences of including a stock effect, our expectation is that it will not alter our qualitative conclusions. To test this expectation, we added a stock

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[18] K_j was drawn with replacement from the set $\{K_1,K_2,\ldots,K_N\}$; D_{ij} was drawn with replacement from the set $\{D_{i1},D_{i2},\ldots,D_{iN}\}$; and patch areas were drawn with replacement from the set of patch areas.

effect where marginal cost in patch i is θ/X_i, where the scalar θ is interpreted as the density at which it becomes unprofitable to fish.[19] Under this new model, the number and location of the optimal reserve network in a coordinated TURF system remains the same (18 TURFs are in reserve). We also explored the effects of arbitrary MPA closures on profits and abundance, for both the uncoordinated and coordinated TURF fisheries. Generally speaking, the qualitative results remain unchanged. The quantitative effects of reserves shift slightly, but deviations from the patch closure results in the absence of a stock effect are minor (less than 1 percentage point difference between the patch-by-patch results in Figures 3, 4, 6, and 7 and their counterparts including the stock effect).

4.5. Implementing MPAs when coordination is endogenous

We have shown that when TURF owners fail to coordinate, MPAs often improve economic performance of the property rights fishery. On the other hand, when owners fully coordinate, MPAs may already be privately optimal, and imposing additional MPAs will only decrease profits. But in real systems, full coordination may be difficult to achieve. Instead, coordination mechanisms may be proposed or put in place and TURF owners will self-select in or out of the mechanism. If some owners opt out, then the first best will not be achieved. Because participation is endogenous, the characteristics of fishermen or TURFs that induce owners to opt in (or out) of these coordination mechanisms may be the same characteristics that drive the effects of MPAs, so it is unclear how MPAs will affect profits. A simple example illuminates a powerful result: It turns out that with endogenous participation, MPAs may still improve profits. To see this, consider a simple 2 TURF example, both with the average area and average kelp density of the 48 TURF model. The dispersal kernel is given by: $D_{11} = 0.14 * (1 - \phi)$, $D_{12} = 0.14 * \phi$, $D_{21} = 0$, and $D_{22} = 0.14$, such that a fraction ϕ of larvae from TURF 1 travels to TURF 2, but TURF 2 does not provide any larvae to TURF 1. Under these circumstances, provided $\phi > 0.55$, TURF 2 opts out (preferring harvesting alone to splitting profits with TURF 1), yet an imposed MPA increases system-wide profits. This simple example shows that with endogenous participation, MPAs may still increase system-wide profits.

5. Discussion

What will be the effects of MPAs on profits and conservation in a property rights-based fishery? We study a system in which spatial areas of the sea have been designated as TURFs, where larval dispersal connects stocks across the fishery. For our application, we have considered a species with a

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[19] Here θ is 10 per cent of the carrying capacity density in the least productive patch.

life history similar to kelp bass using oceanographic and ecological data from the southern California coast. We find that the effect of MPAs hinges critically on the existing level of coordination among TURF owners. When TURFs are uncoordinated, owners fail to internalize dispersal externalities, and MPAs (even those arbitrarily placed) often increase individual and system-wide profits, as well as total abundance. This is in stark contrast to the empirical results of Smith and Wilen (2003), who find that imposing MPAs on a limited-entry fishery will only decrease profits, but is consistent with some of the theoretical results in Sanchirico and Wilen (2001) and Sanchirico and Wilen (2002).[20] On the other hand, we find that when owners are fully coordinated, the first-best spatial harvest pattern is achieved, and some TURF owners voluntarily create private MPAs. Siting additional closures only reduces TURF-specific and system-wide profits and may in some cases even reduce abundance.

A few caveats are in order. First, we consider only extreme cases—full coordination and no coordination, via full profit sharing. A generalization would allow partial profit sharing, where a percentage of profits are pooled, and the remainder is retained by the owner (Uchida 2007). This, or other coordinating mechanisms, may affect our results concerning the impact of MPAs on economic and conservation performance. Second, our economic model is simple: costs are linear in harvest, price is constant, and we use a zero discount rate. A generalization could allow for downward sloping demand or a positive discount rate that would require dynamic solutions to transition to steady state. While these generalizations are undoubtedly more realistic, and would affect our quantitative answers, we do not believe they will qualitatively affect our main conclusions. Finally, we have examined a single species model with density-dependent recruitment, adult survival, and an association with kelp cover. Species with other life history traits might affect our quantitative results, but are also unlikely to affect the qualitative conclusions. Examining a multispecies fishery, in which TURF owners had exclusive rights to harvest multiple species in their TURFs, might affect results. If harvest can be costlessly selective (e.g. for sedentary adults who are easy to identify and are harvested by hand), then we can regard each species independently, and 'closures' would be species-specific. Allowing for multispecies biological interactions would substantially complicate this model.

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[20] One explanation of the difference between our results and Smith and Wilen (2003) is that urchin and kelp bass have significantly different life history traits. While it is true that biology and dispersal are crucial determinants of reserve success, a more compelling explanation is that the existence of spatial property rights prevents the spatial rent dissipation that occurs in open-access and limited-entry settings, increasing the likelihood of increased fishery profits. Because the spatial rent dissipation problem is handled by the enforced TURF boundaries, MPAs can be thought of as a second-best correction of the market failure stemming from the spatial externality of larval dispersal.

As we move towards property rights-based fisheries management, and in particular, spatial property rights (TURFs), the level of coordination among owners will drive economic and ecological performance of the fishery. If coordination is complete, private MPAs may emerge—additional MPAs reduce profits, and may even reduce abundance of fish. However, to the extent that coordination between TURF owners is incomplete, strategically sited MPA networks are likely to be an effective complement to spatial property rights-based fisheries.

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