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# **The Impacts of Marine Reserves on Limited-Entry Fisheries**

James N. Sanchirico and James E. Wilen

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# **The Impacts of Marine Reserves on Limited-Entry Fisheries**

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## **Abstract**

We utilize a spatial bioeconomic model to investigate the impacts of creating reserves on limited-entry fisheries. We find that reserve creation can produce win-win situations where aggregate biomass and the common license (lease) price increase. These situations arise in biological systems where dispersal processes are prevalent and the fishery prior to reserve creation is operating at effort levels in a neighborhood of open-access levels. We also illustrate that using strictly biological criteria for siting reserves (e.g., setting aside the most biological productive areas) will likely induce the most vociferous objections from the fishing industry. In general, we find that the dispersal rate and the degree the patches are connected play a significant role on the net impacts on the fishing sector.

**Key Words:** fisheries; limited-entry; marine reserves

**JEL Classification Numbers:** Q22 and R10

**This paper is forthcoming in *Natural Resource Modeling*.**

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# **The Impacts of Marine Reserves on Limited-Entry Fisheries**

James N. Sanchirico and James E. Wilen\*

## **Introduction**

In May of 2000, U.S. President Clinton signed an executive order directing agencies responsible for marine conservation to develop a plan to establish a comprehensive system of marine reserves within U.S. coastal waters. This was rightly hailed as a major victory by marine conservationists and scientists who have been vocal supporters of marine reserves for close to a decade. To long-time observers of the politics of fisheries management in the U.S., this action by the President is viewed by many as miraculous in a system more typically regarded as sluggish, provincial, and not prone to radical change. In many ways, the very rapid acceptance of the concept of marine reserves in U.S. policy is more reminiscent of radical executive order innovations in Canada thirty years ago establishing limited-entry for the first time, and in New Zealand twenty years ago establishing individual transferable quota programs.

Despite the fanfare, it would be premature for proponents of reserves to declare victory before the details are worked out. With marine reserves, the devil will certainly be in the details, and whether the U.S. ends up with anything close to what is envisioned by marine conservationists will certainly depend upon a lengthy process of debate over different design options, scales, and visions. And this debate will reflect strengths of opinions among different stakeholder groups: from scientists, to representatives of the conservation community, to fishermen and others who depend upon current configurations of regulations for their livelihoods. Fishermen will clearly play an important role in the political process, since the costs and benefits to them are much more tangible than the important but less easily quantifiable conservation benefits held by the public at large.

This paper examines the question: how will various marine reserve options affect fishermen participating in limited-entry fisheries? We ask the question from the fishermen's

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perspective since we believe that the fishing industry will be the most likely and most effective opponent of reserves, if any group emerges to oppose them. In an open political system like that present in the U.S., the political process will eventually craft compromises and tradeoffs that reflect perceptions of gains and losses, and industry opposition could mobilize to block plans that might have large negative impacts on fishermen and coastal communities. Alternatively, the process will favor those plans that seem to involve “win-win” situations in which fishermen can gain from reserves, or situations in which reserve costs to the industry are relatively low.<sup>1</sup>

We examine fisheries characterized by limited-entry regulatory schemes for several reasons. First, most important fisheries in developed countries worldwide are either subject to some kind of limited-entry program or are likely to have such programs in the near future. Second, we expand on some related work that addresses similar questions, but under the assumption of open-access institutions.<sup>2</sup> Third, there are some interesting issues related to the manner in which license prices themselves are good signals about the overall economic health of the fishing industry, and hence good gauges of the economic impact of reserves.

In the next section we develop a simple spatial bioeconomic model of a limited-entry fishery harvesting a metapopulation. The model allows us to depict various behavioral characteristics of both the fishing industry and the population biology. The model is used to simulate the introduction of a marine reserve in a patchy biological system. We focus on license prices and on aggregate industry rents to characterize the impacts of reserves. The last section summarizes and discusses further issues for investigation.

## The Model

The foundations of the model employed here are developed in more detail in Sanchirico and Wilen [1998, 1999a]. The basic structure combines a standard biological metapopulation model with a reformulation of economic models developed by both H.S. Gordon [1954] and V. Smith [1968]. The complete integrated bioeconomic model can be written as:

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<sup>1</sup> Note that we are taking a political economy perspective rather than a welfare economics perspective here.

<sup>2</sup> The literature on the potential impacts of marine reserves is expanding rapidly, and an in-depth literature review is beyond the scope of this paper. Instead we point the interested reader to the following biological review articles: Dugan and Davis [1993]; Roberts and Polunin [1991]; Carr and Reed [1993]; Allison, Lubchenco and Carr [1998], Carr and Raimondi [1998]; Palumbi [1999], Boersma and Parrish [1999]; and the following economic review articles: Farrow [1996]; Thomson [1998]; Sanchirico [2000].

$$\dot{x}_i = f_i(x_i)x_i + d_{ii}x_i + \sum_{\substack{j=1 \\ j \neq i}}^n d_{ij}x_j - h_i \quad \forall i = 1, \dots, n \quad (1)$$

$$\dot{E}_i = s_i R_i(E_i, x_i) + \sum_{\substack{j=1 \\ j \neq i}}^n s_{ij} [R_i(E_i, x_i) - R_j(E_j, x_j)] \quad \forall i = 1, \dots, n \quad (2)$$

The first component is the biological system, which depicts the evolution of biomass levels in  $n$  separate biological patches where  $x_i$  is the biomass level in patch  $i$ ,  $f_i(x_i)$  is the per capita growth rate in patch  $i$ ,  $h_i$  is the harvest rate in patch  $i$ ,  $d_{ii}$  is the rate of emigration from patch  $i$  ( $d_{ii} < 0$ ), and  $d_{ij}$  is the dispersal rate between patches  $i$  and  $j$ . The biological system depicted here is a standard linear metapopulation model in which there are  $n$  discrete patches in space, each of which is characterized by "own" patch dynamics as well as linkages to other patches.<sup>3</sup> In this formulation, own growth is separable from dispersal, and the dispersal process can be flexibly modeled via appropriate choice of the coefficient  $d_{ij}$ .<sup>4</sup> In this paper, we follow the long tradition in the ecology literature depicting the dispersal processes as density dependent.<sup>5</sup> In density dependent dispersal processes, biomass flows between patches in a manner dependent upon the relative densities of each patch. The simplest representation of a density dependent dispersal process depicts the dispersal mechanism between patch one and two as  $d_{11}x_1 + d_{12}x_2 \equiv b(x_2/k_2 - x_1/k_1)$ , and between patch two and one as  $d_{22}x_2 + d_{21}x_1 \equiv b(x_1/k_1 - x_2/k_2)$ .

The second component is a behavioral model of a harvesting industry operating over a heterogeneous environment that depicts the fleet responding to economic variables over both time and space. Let  $E_i$  denote the patch-specific levels of effort in each patch  $i$ , and let  $R_i(E_i, x_i)$  be corresponding rents (or profits) expected in patch  $i$ . Then we can hypothesize a simple sluggish adjustment process in which the level of effort,  $E_i$  in patch  $i$ , changes according to equation 2. In this specification, effort in patch  $i$  changes in response to the level of rents  $R(E_i, x_i)$

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<sup>3</sup> See, for example, the review articles by Levin [1976]; Hastings and Harrison [1994]; and Hanski [1999].

<sup>4</sup> This lumped parameter representation is itself very stylized since it ignores important aspects of real population growth and dispersal dynamics including age- and size-specific mechanisms, selectivity issues, and more complicated spawner/recruit processes. However, it is analytically tractable whereas richer models must be analyzed using simulation methods.

<sup>5</sup> The literature on reserves also discusses other formulations that depict uni-directional flow, generally assumed to be the result of oceanographic processes such as currents, winds, and temperature. These models are often referred to as sink-source models (Pulliam [1988]; Tuck and Possingham [1994]), and they characterize dispersal flow as a process that is independent of population densities in the sinks.

vis à vis outside opportunities (captured in the first term), and net dispersal (depicted by the second term). The second term consists of a sum of pairwise spatial dispersal rates, each proportional to rent differentials across space between the patch in question and alternative patches. Hence there will be dispersal from patch  $j$  into patch  $i$  if rents in  $i$  exceed those in  $j$ , and dispersal to  $j$  from  $i$  if the net difference is negative. At any point in time, patch  $i$  may be contributing to a subset of patches experiencing higher relative rents and drawing from another subset experiencing relatively lower rents. For the system as a whole, these spatial forces tend to redistribute effort over space in a manner that, in the long run, equalizes net rents across all patches.<sup>6</sup>

The above system (equations 1 and 2) is capable of addressing a variety of questions about how fishing efforts will distribute itself over time and space, and how that distribution of absolute and relative effort will affect the biological system through own growth and dispersal. To close the model we need to specify the rent functions in ways that characterize institutional features of the fisheries that are of interest. In Sanchirico and Wilen [1999a] we assumed that the fishery is an open-access fishery in which effort flows into the fishery and across space in a way that ultimately dissipates rent in equilibrium. In particular, if we assume a Schaefer production function ( $h_i = q_i E_i x_i$ , where  $q_i$  is the catchability coefficient), constant patch-specific costs per unit effort ( $c_i$ ), and a common vessel capital opportunity cost ( $\pi$ ), we have

$$R(E_i, x_i) = pq_i E_i x_i - (c_i + \pi)E_i \quad (3)$$

as the aggregate rent function for patch  $i$ , where  $p$  is the ex-vessel price. With these patch-specific rent functions inserted into the system above, we can examine both transition paths and equilibria of various systems with different biological and economic characteristics.<sup>7</sup>

The spatial and intertemporal bioeconomic system outlined here is particularly useful for examining the impacts of reserve formation (Sanchirico and Wilen [1998]). If we begin, for example, with a system in which harvesters freely move across all patches in a biological system, we can characterize the nature of the exploited equilibrium that would emerge, as well as the

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<sup>6</sup> This will not be the optimal way to distribute effort over space, of course, since it is the outcome of a myopic, open-access process. It will also be the case that too much effort will be drawn into the whole system since effort will be responding to average and not marginal rents.

<sup>7</sup> For example, Sanchirico and Wilen [1999a] show how the spatial distribution of effort and the total amount of effort in an open-access system changes with different dispersal mechanisms, and with different kinds of biological and economic heterogeneity.



nature of the adjustment process to that exploited equilibrium. In this (pre-reserve) equilibrium, the level of own biological growth in each patch will be exactly offset by the total net dispersal between the patch and other linked patches, and the harvest in the patch in question. In addition, net rents will be identically equal to zero in each patch, leading to an economic equilibrium over time and space. The pre-reserve bioeconomic steady-state can be formally written as

$$\begin{aligned} \dot{x}_i^{set} = 0 &\Rightarrow f_i(x_i)x_i + d_{ii}x_i + \sum_{\substack{j=1 \\ j \neq i}}^n d_{ij}x_j = h_i \quad \forall i=1, \dots, n \\ \dot{E}_i^{set} = 0 &\Rightarrow R_i(E_i, x_i) = 0 \quad \forall i=1, \dots, n \end{aligned} \quad (4)$$

Note that while the biological dispersal coefficients ( $d_{ii}$  and  $d_{ij}$ ) affect the equilibrium vector of biomass and effort levels in each patch, the economic response parameters ( $s_i$  and  $s_{ij}$ ) only affect the speed of response to equilibrium. This occurs because the economic system equilibrates when net rents in each patch are zero, and the conditions that generate zero rents are independent of the response rates, as in the Vernon Smith model of a single patch.

### Reserve Creation in a Limited-Entry Fishery

With straightforward modifications of the rent functions, the system discussed above can be used to depict a fishery that is regulated by a **limited-entry licensing** system, with the licenses placed on vessels. The simplest way to see this is to note that the licensing system will create rights that have some value to existing and potential participants. In equilibrium, the price of licenses will rise until the opportunity cost is equal to the anticipated production rents in the fishery. Let  $L$  be the equilibrium license **lease** price in a limited-entry system, that is, the amount that a potential entrant would be willing to pay an existing participant to lease his/her vessel-specific license for a period. In equilibrium, we will have

$$R(E_i, x_i) = pq_i E_i x_i - (c_i + \pi)E_i - LE_i = 0 \quad (5)$$

across all patches, where the (common) license lease price is endogenously determined and is a function of the total number of licenses outstanding.<sup>9</sup>

Thus, the license lease price rises to eliminate rents at two margins. The first margin is related to outside opportunities for the vessel capital in question. In equilibrium, owners of

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<sup>9</sup> As it is currently modeled, the license price is equivalent to a charge per unit of effort.

vessel capital will be indifferent between participating in the alternative fishery and earning  $\pi$  per unit capital, or participating in the limited-entry fishery by paying the lease price  $L$  and earning  $pq_i x_i - (c_i + \pi)$  per vessel in the fishery. The second margin exists between any patch  $i$  and another alternative patch  $j$ . In the full spatial equilibrium, a vessel owner facing lease price  $L$  will be indifferent between fishing in patch  $j$  and in patch  $i$ , so that

$$pq_i x_i - (c_i + \pi) = L = pq_j x_j - (c_j + \pi).^{10}$$

To examine the implications of reserve creation within this system of limited-entry licensing, we develop a simple three-patch exercise. In this exercise, we compare two systems, one without a reserve and one with a reserve located in patch three.<sup>11</sup> Assuming that the own growth functions in each patch are quadratic, the system of equations that define the steady-state equilibrium for each of the two cases are in Table 1.

We use these systems to compute equilibrium values for biomass, harvest, effort in each patch and the (common) license price. Understanding the impacts of reserves on license prices is important, because license values are indicative of the total rents in the system. Any policy that increases aggregate rents in the industry will also increase license values; policies that decrease rents will decrease license values.

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<sup>10</sup> This particularly simple structure is due in part to the fact that the rent function is linear in  $E$ . This makes marginal rents equal to average rents, which simplifies the nature of the rent-dissipating relationships.

<sup>11</sup> We assume that the biological and economic system parameters are unchanged after an area is set aside. This assumption might not hold in practice, however. For example, the intrinsic growth rate of the stock in the reserve might increase after the area is set aside due to the elimination of harmful harvesting practices. Another possibility is that the costs of harvesting in the open patches might increase due to an increase in congestion.

**Table 1: Two Systems of Equations Defining the Steady-State Equilibrium**

EQUATION (6): WITHOUT A RESERVE	EQUATION (7): WITH A RESERVE
$r_i x_i (1 - \frac{x_i}{K_i}) - d_{ii} x_i + \sum_{j=1}^2 d_{ij} x_j - q_i x_i E_i = 0, i=1,2,3$	$r_i x_i (1 - \frac{x_i}{K_i}) - d_{ii} x_i + \sum_{j=1}^2 d_{ij} x_j - q_i x_i E_i = 0, i=1,2$
$p q_i x_i - (c_i + \pi) - L = 0 \quad i=1,2,3$	$r_k x_k (1 - \frac{x_k}{K_k}) - d_{kk} x_k + \sum_{j=1}^2 d_{kj} x_j = 0 \quad k=3$
$E^{TOT} = \sum_{i=1}^3 E_i$	$p q_i x_i - (c_i + \pi) - L = 0 \quad i=1,2$
	$E^{TOT} = \sum_{i=1}^2 E_i$

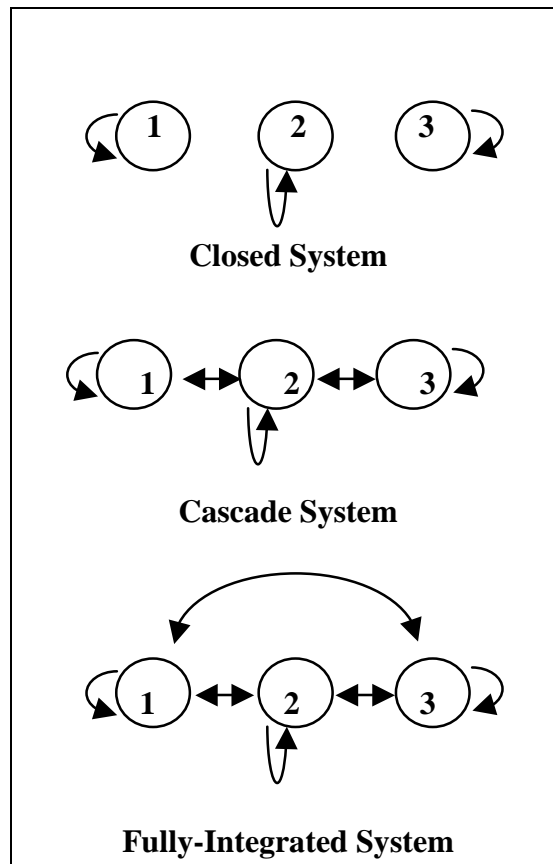
In the remainder of this section, we discuss the impacts of reserve creation within closed, fully-integrated, and cascade systems (see Figure 1). As it turns out, we can analytically derive the results for the closed system. In the more complex and linked systems however, the systems of equations are non-linear. We numerically simulate the impacts of reserve creation in these cases.<sup>12</sup>

### **Closed Biological System**

As Sanchirico and Wilen [1998] have shown in the case of an open-access fishery, reserve creation in a **closed** metapopulation system increases aggregate biomass but fails to provide any benefits to the industry. In fact, due to the absence of spillover from the reserve, the reduction in harvest is greater than in the fully-integrated and cascade systems. Intuitively, we would expect that in the limited-entry setting, the open-access results would hold qualitatively, because there still is no mechanism for biological spillover effects. In fact they do. The steady-state levels for the closed case are provided in Table 2. While this case is very restrictive, we find that it illustrates rather clearly the necessary mechanisms for the industry to benefit from closures.

<sup>12</sup> In the cases where the n-patch biological system is fully integrated, for example, the equation for the license price is a n+1 degree polynomial.

Figure 1: Biological Systems\*



\* The arrows represent the own and dispersal feedback mechanisms within and between the patches.

We solve for the steady-state equilibrium levels of biomass, effort, and license price in this setting by using the fact that  $pq_i x_i - (c_i + \pi) = L = pq_j x_j - (c_j + \pi)$  and the steady state equations (equations 6 and 7). As is evident in Table 2, the results illustrate not only the impact of a reserve, but also differences between equilibria in the open-access system and a limited-entry licensing system. Of course when the amount of effort limited in the fishery ( $E^{\text{TOT}}$ ) is equal to the aggregate open-access levels, then the biomass and effort levels equal the open-access levels. In this case, all rents are dissipated and the license value is zero. Thus, the open-access aggregate effort level provides a natural upper bound to the total amount of effort. As the amount of total system effort is constrained to be smaller than the open-access equilibrium level, the “shadow price” on the constraint (the license value) rises. For any given amount of effort in the system, there will be a unique license value of  $L$ , and that value will be equal to the (common) rent level in all patches.

**Table 2: Closed System Equilibrium Levels with and without a Reserve Located in Patch Three**

EQUATION(8): WITHOUT A RESERVE	EQUATION (9): WITH A RESERVE
$x_i = x_i^{OA} + \frac{1}{q_i \sum_{i=1}^n \frac{r_i}{q_i^2}} [\sum_{i=1}^3 E_i^{OA} - E^{TOT}]$ $E_i = \frac{r_i}{q_i} (1 - x_i^{OA} - \frac{1}{q_i \sum_{i=1}^3 \frac{r_i}{q_i^2}} [\sum_{i=1}^3 E_i^{OA} - E^{TOT}])$ $L_{dij=0}^{ss} = \frac{P}{\sum_{i=1}^3 \frac{r_i}{q_i^2}} [\sum_{i=1}^3 E_i^{OA} - E^{TOT}]$	$x_i = x_i^{OA} + \frac{1}{q_i \sum_{i=1}^2 \frac{r_i}{q_i^2}} [\sum_{i=1}^2 E_i^{OA} - E^{TOT}], i = 1, 2$ $x_k = K_k, k = 3$ $E_i = \frac{r_i}{q_i} (1 - x_i^{OA} - \frac{1}{q_i \sum_{i=1}^2 \frac{r_i}{q_i^2}} [\sum_{i=1}^2 E_i^{OA} - E^{TOT}]), i = 1, 2$ $E_k = 0, k = 3$ $L_{dij=0}^{ss} = \frac{P}{\sum_{i=1}^2 \frac{r_i}{q_i^2}} [\sum_{i=1}^2 E_i^{OA} - E^{TOT}]$
<p>where <math>E_i^{OA} = r_i(1 - \frac{c_i + \pi}{pq_i})</math> and <math>x_i^{OA} = \frac{c_i + \pi}{pq_i}</math></p>	

As it turns out, the implication of shutting down patch three in this setting is rather straightforward. The biomass density level there will equilibrate at its carrying capacity and the effort level will be zero. In the open patches, the more constrained the total effort, the higher the biomass and the system-wide license price, and the lower the patch-specific effort levels in remaining open areas. As discussed earlier, in a licensed limited-entry system, the license price provides a signal on the impact of policies on fishery rents. If the license price increases after patch three is closed, then fishery rents have increased due to the closure. Of course, if the license price decreases, then rents have decreased.

We can illustrate these results either in terms of aggregate fishery rents or equilibrium license prices. The function depicting aggregate license values (equilibrium license price times the number of licenses outstanding) has a maximum at the total effort levels that maximize

rents.<sup>13</sup> In the pre-reserve system, for example, the optimal number of licenses is

$$E^{TOT*} = \frac{1}{2} \sum_{i=1}^n E_i^{OA} .$$

Post reserve creation, the optimal number of licenses decreases by  $1/2 * E_3^{OA}$ . In a biologically closed system, generally the post-reserve license value function is everywhere lower than the pre-reserve function (see Figure 2 panel A), suggesting that reserves in a closed system do not improve economic conditions for fishermen. An implication of this is that the rent-maximizing level of effort after reserves are created is at a lower aggregate effort level, suggesting that a reserve policy designed to maximize industry rents may have to employ a buy-back or other effort-reducing scheme to eliminate excess effort.

### **Linked Metapopulation Systems**

Upon reflection, it should not be surprising that creating a reserve in a complete decoupled system does not increase aggregate rents to fishermen. This is because there is no direct fisheries payoff to the closure in a biological system in which there is no dispersal. For fishermen to benefit from a closure, the closed patch must contribute some spillover of biomass to the remaining open patches, and that requires some dispersal. Accordingly, in this section, we simulate a closure in patch 3 but in **fully-integrated** and **cascade** systems in which there is density-dependent biological dispersal between the patches. In the cascade system, closing patch 3 corresponds to closing a patch on the edge of the system where the biomass only directly interacts with patch 2. Both of these biological structures illustrate circumstances that can lead to potential "win-win" scenarios.

For the fully-integrated and cascade systems, we numerically simulate the derived demand for licenses and the maximum aggregate rent curves pre and post reserve creation. We continue to assume that the own growth functions in each patch are quadratic with equal intrinsic growth rates and carrying capacities ( $r=0.8$ ,  $K=1$ ), and with dispersal rates ( $b=0.4$ ) equal to half the own growth rate. We initially introduce heterogeneity into the system by assuming that patch 3 is a relatively higher cost patch to fish than the other patches ( $c_3=13.0$  and  $c_1=c_2=11.0$ ). The

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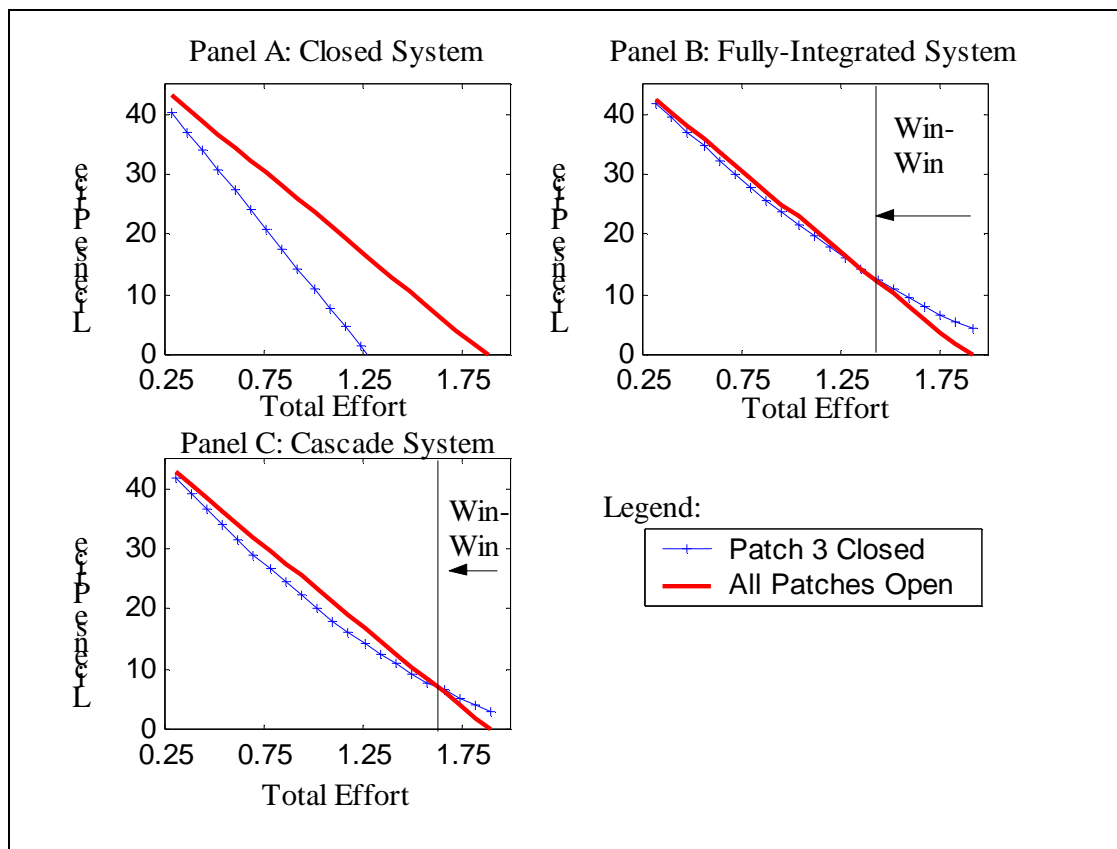
<sup>13</sup> In this case, the program for determining the level of aggregate effort that maximizes aggregate rents is

$$\max_{E^{TOT}} L_{d_{ij}=0}^{ss} E^{TOT} = \frac{P}{\sum_{i=1}^n \frac{r_i}{q_i^2}} [\sum_{i=1}^n E_i^{OA} - E^{TOT}] E^{TOT} .$$

price is assumed identical across all patches ( $p=65$ ) and catchability coefficients are normalized to 1.0.

The simulation finds values of effort and biomass across all patches that bring the system into a bioeconomic equilibrium, given some fixed amount of effort ( $E^{TOT}$ ). The results are presented in Figures 2 and 3. For comparison purposes, we simulate a reserve in the biologically closed case, which complements our earlier analytical results. For all cases, Figures 2 and 3 can be read as follows. Suppose that we have a limited-entry system with some reasonably restricted level of effort such as 1.08. Then, before a reserve is implemented in the biologically closed case (Panel A, Figures 2 and 3), license prices would have equilibrated at a level of 21.52 per unit of effort, and aggregate license values will be 23.31. After patch 3 is closed, license values per unit effort fall to 7.85, and aggregate license values (rent in the system) fall to 8.51.

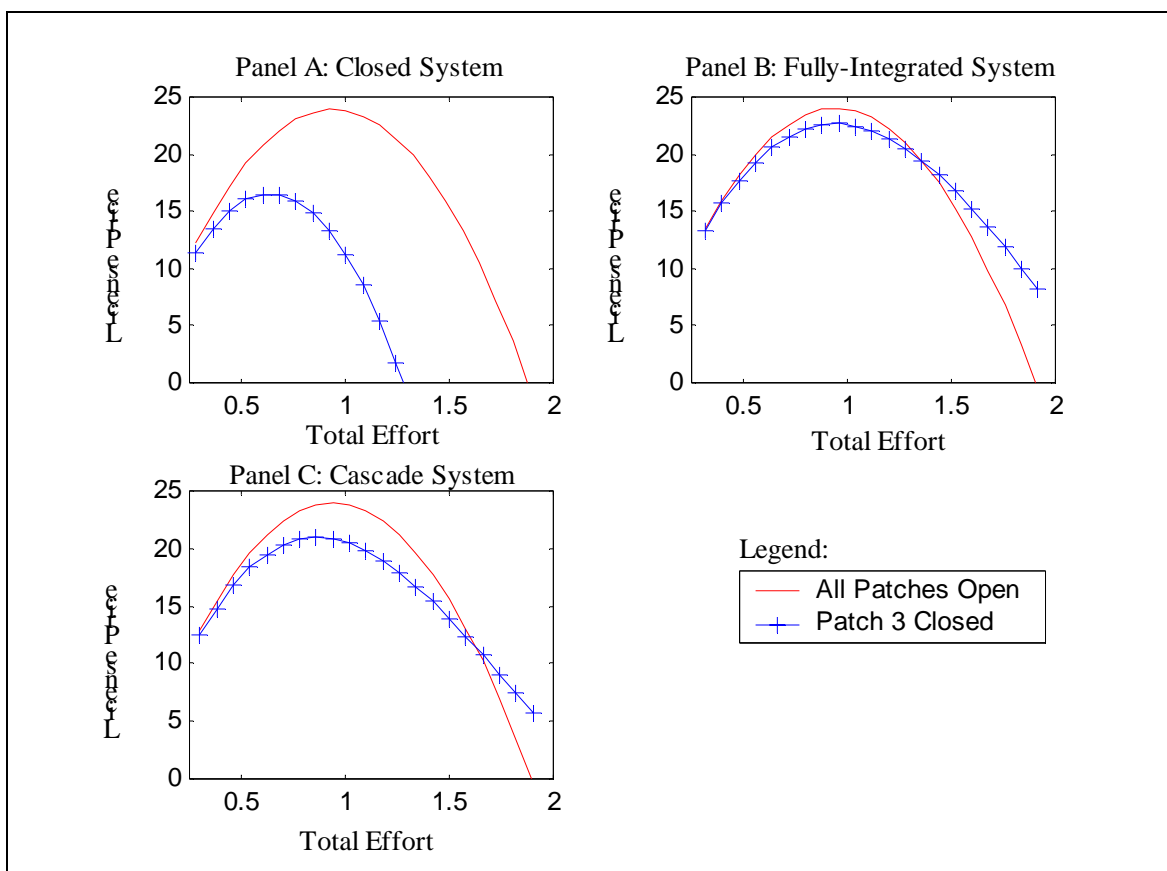
**Figure 2: Derived Demands for Effort with and without a Reserve in Patch 3**



We first discuss the impacts of closing patch 3 within a **fully-integrated** system in which there is density-dependent biological dispersal between the patches. Panel B in Figures 2 and 3

shows the impact of reserve creation in this kind of biological system. It is important to emphasize several important results, including some comparisons of the fully-integrated system with the closed case. First, the difference between system rents before and after the creation of a reserve is smaller than in the closed system. Second, over most of the range of total effort, a marine reserve costs the industry some rents. Thus while dispersal from the closed patch helps make up for the closure, on net the increase in yields after the closure is not sufficient to compensate for the lost opportunities in the closed patch. However, and interestingly, at high initial levels of effort, a reserve actually increases license values, suggesting possible “win-win” scenarios. This is consistent with Sanchirico and Wilen [1998] who show that “win-win” reserve designs are more probable when the closed patch is over-depleted, and when dispersal occurs after closure.

**Figure 3: Maximum Aggregate Rents with and without a Reserve**



While the closed and fully-integrated cases define the bounds in terms of the degree of biological connectedness, the cascade system illustrates the impacts of siting reserves in



intermediate cases. In addition, this case illustrates how the placement of a reserve can affect the overall outcome. Recall that in this case, patch three is only directly connected to patch two, which is the center patch. From panel C of Figure 2, it is evident that the range of effort levels corresponding to the "win-win" scenario is smaller than in the fully-integrated setting, everything else equal.

Therefore, while locating a reserve on an edge of the system could yield positive economic and biological benefits, the magnitude of the benefits is less than what would arise when an area that is more connected to the rest of the system is set aside. This result stems from a spatial Le Chatelier effect, in which the cascade system is more constrained than the fully-integrated system but less constrained than the closed system. As Figures 2 and 3 illustrate, the expected effects of reserves depend not only on the dispersal rate, as many have noted, but also on the ecological structure of the system where reserves are sited.<sup>14</sup>

### Which Patch Should Be Closed?

It is clear that whether a reserve sited in a particular location or fishery will yield a win-win situation depends on the current biological and economic conditions. It is also clear that opposition to reserves by fishermen could be greatest in cases where they have the most to lose. Given the political-economy realities of siting reserves, a worthwhile exercise is to try to determine characteristics of patches where reserves are most likely to have the least objection.

In this section, we illustrate the impacts of siting reserves when there exists a patch that is more biologically productive and when there exists a lower cost patch. We focus on these two cases for a couple of reasons. First, many proponents of reserves treat the reserve selection issue as if it were one of simply finding and closing inherently high productivity areas. If this was the

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<sup>14</sup> Many authors have focused on the role of dispersal rates and rightly so, as it is a critical component of a metapopulation system and a key determinant of the impacts of marine reserves beyond their boundaries (Polacheck [1990], Carr and Reed [1993], Holland and Brazee [1996], Allison, Lubchenco and Carr [1998], Carr and Raimondi [1998], Hannesson [1998], Sanchirico and Wilen [1998], Palumbi [1999], and Boersma and Parrish [1999]). As Sanchirico and Wilen [1998] have shown for a win-win to occur under open-access conditions, the dispersal rate should be neither too high nor too low. Too low is obvious because as the dispersal rate goes to zero the linked systems approach the closed system. Too high, on the other hand, is less clear. When the dispersal rate is too high, they find that the increase in biomass within the protected area is lower, thereby decreasing the magnitude of the biological spillover effect and decreasing the probability that the opportunity cost of forgone harvest is exceeded. In this analysis, dispersal rates play a similar qualitative role and therefore, we have focused on the structure of the dispersal system rather than on dispersal rates.

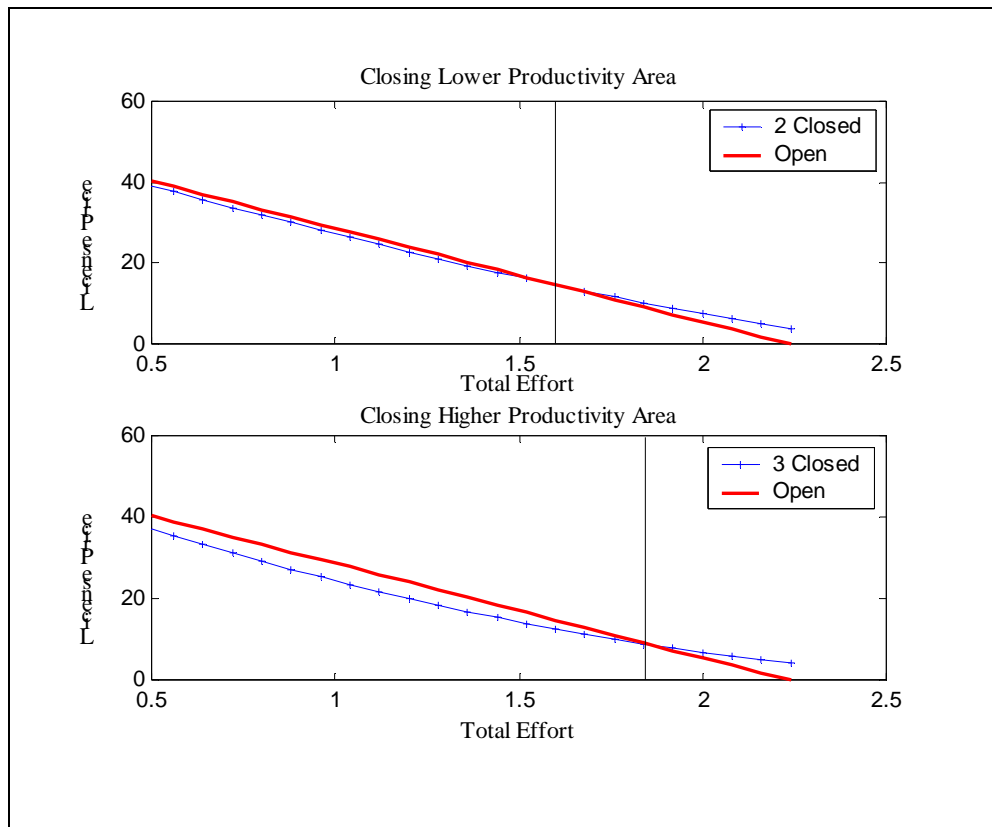
case, then we would expect that closing high productivity areas will yield a "win-win" scenario, or at least dominate (higher license prices) closing lower productivity areas, everything else equal. Second, under open-access conditions, Sanchirico and Wilen [1998] found that closing the most profitable patch provided the greatest chance for aggregate harvests to increase. This result was due to the fact that under open-access, the most profitable area is over-exploited (lower harvests) and shutting it down results in the lowest opportunity cost. In a limited-entry setting however, both the amount harvested and the net returns per unit of effort in the fishery determine whether aggregate license prices might increase.

To investigate the impacts of closing high productivity areas and low cost areas, we simulate the closure of patch 3 in a fully-integrated system, but with a new assumption that the patch has a growth rate or cost 1.5 times greater than patches 1 and 2. We then compare the results to a closure in patch 2, which is assumed to have a lower growth rate and cost, everything else equal.<sup>15</sup> To keep the analysis simple, when we simulate the biological case, we assume that there exists no economic heterogeneity so that, in terms of the economic parameters, each patch is identical. And when we simulate the economic case, we assume that there exists no biological heterogeneity. This allows us to focus specifically on the questions at hand. Of course, in practice these conditions are most likely intertwined. For example, in many fisheries, there is anecdotal evidence that the areas with highest biologically productivity are also areas where returns per unit of effort are the highest .

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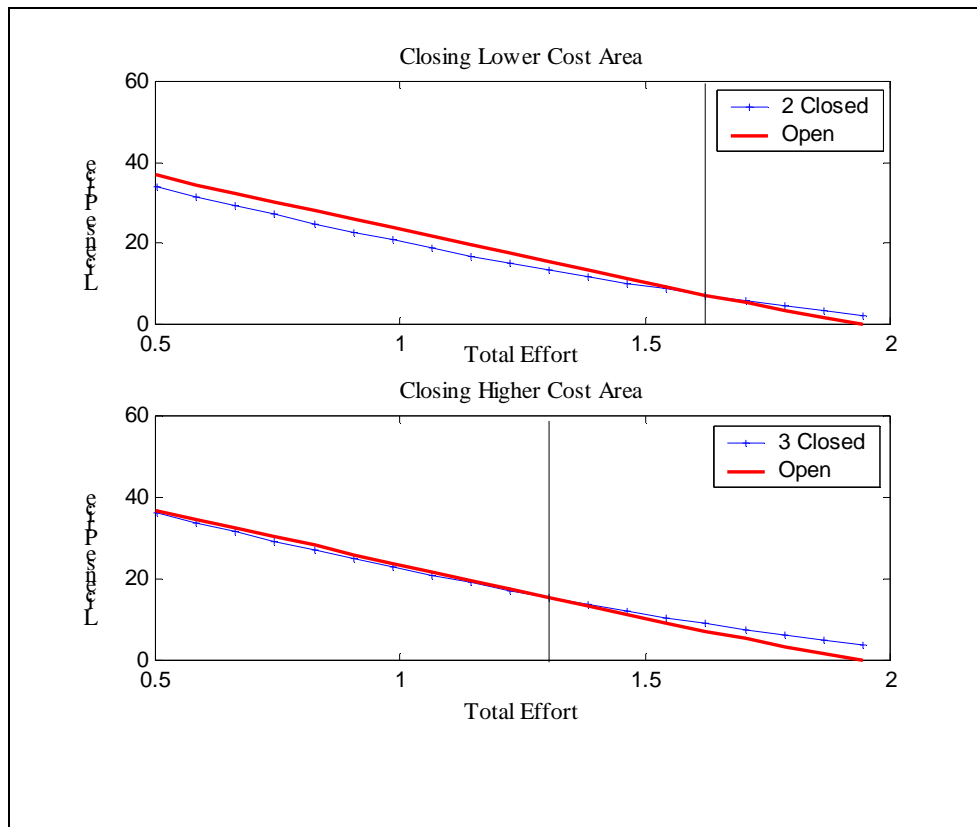
<sup>15</sup> Note that both closures are simulated with the following growth rates  $r_3=1.5*r$ ,  $r_2=r_1=r$ .

Figure 4: Closing High vs. Low Productivity Areas



The results on the impacts of closing high versus low productivity areas are presented in Figure 4. Under the chosen parameters, both cases result in win-win scenarios over ranges of total effort whereby the systems are severely overexploited. Interestingly, the range of effort levels over which this occurs is **larger** when the lower productivity area is closed. In fact, over the whole policy-relevant range of effort levels, the license price is higher when the lower productivity area is closed. Since license prices represent the value of a policy in terms of fishery rents, these results suggest that closing low productivity areas might provide greater returns to the fishermen than higher productivity areas, everything else equal. This result was also found in Sanchirico and Wilen [1998], and was attributed to the fact that high productivity areas provide the highest pre-reserve returns to fishermen and hence the highest opportunity costs of closures. As it turns out, in many cases similar biological gains can be accrued by closing off lower productivity areas, while at the same time lowering the opportunity costs of the closure to the fishermen.

Figure 5: Closing High vs. Low Cost Areas



Next, we investigate the implications of siting reserves when there exist differences in costs that could stem from differences in steaming costs and oceanographic conditions (e.g., strong currents and substrate characteristics that prohibit the use of certain gear types). As evident in Figure 5, the range over which the win-win occurs is larger when the higher cost area is closed than when the lower cost area is closed, everything else equal. Also, the differences between the two cases are smaller over the entire range of effort levels. We find, therefore, that it is no longer necessarily the case that closing the low cost area will yield a greater chance of a win-win situation.<sup>16</sup> In fact, in both cases, aggregate catches actually decrease under the parameters assumed. If total catches decrease, then how does the license price increase? Recall that the license price summarizes all of the available information in the fishery including ex-

<sup>16</sup> In Sanchirico and Wilen [1998], a win-win situation occurred when both aggregate catches and biomass increased. Aggregate catches are used as indicators for the impact of reserves on the open-access fishery because there is no long-run economic change from reserves; rents are dissipated both before and after reserve creation.

vessel prices, growth rates, harvest levels, and costs per unit of effort. In this case, the reserve shifts the spatial distribution of the catch to more profitable areas. The benefits of this shift, as measured by the license price, more than compensate for the loss in total catch, at least when total effort is in a neighborhood of open-access levels.<sup>17</sup>

These results suggest three important points. First, economic factors should be considered in siting decisions, if for no other reason than to reduce the opposition to sensible reserve plans. Second, some of the conventional wisdom that might be suggested from purely biological objectives (e.g., to close high productivity patches) may be reversed when one considers the economic costs to the industry of reserve siting. Third, if placed appropriately, reserves can improve the economic conditions of a fishery that is managed with non-spatially explicit instruments.

## Conclusions and Discussion

This paper considers the manner in which the establishment of a marine reserve in a limited-entry licensing system might affect fishermen. We utilize a simple metapopulation-based biological model and append a behavioral model of fishermen that hypothesizes spatial movement in response to rent differentials. We simulate a limited-entry system in which there is a fixed amount of total effort that then distributes itself over space, determining an endogenous license price reflecting the shadow value of another unit of effort.

There are several qualitative conclusions that can be drawn from this simple analysis. First, license values are a gauge of aggregate system profits and hence, in principle, they can be used as a measure of the impact of reserves on the fishing industry. If a reserve is implemented that makes fishermen worse off in the aggregate, that outcome will be signaled with a drop in aggregate equilibrium license values and the reverse will happen when fishermen's incomes are improved. Given the almost infinite range of design options possible for a system of reserves, it seems politically expedient to look for options that have few negative or even positive impacts on fishing profits.

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<sup>17</sup> It is important to point out that the effort distribution with a common license price does not correspond in general to the optimal distribution. As a result, there is an opportunity for a reserve to shift effort towards a more "economically favorable" distribution than that which occurred prior to the reserve. In order to arrive at an optimal spatial distribution, policymakers would need to introduce spatially explicit license prices (Sanchirico and Wilen [1999b]). In this case, it would not be possible for a reserve to redistribute effort in a manner that would increase the license price.

Second, we show that the nature of the spatial dispersal system is important to the success potential of reserves. Closed systems increase aggregate biomass, but they cannot increase aggregate catch because there is no dispersal from the reserves. Open systems with linkages fare better. Generally in open systems, a reserve decreases rents and causes license values to fall. However, there are some circumstances in which a reserve actually increases rents. These are when the initial pre-reserve equilibrium is close to the open-access equilibrium (such as when the limited-entry program barely limits entry), and when the high cost patch is designated the reserve. Thus a “win-win” situation requires special biological and economic preconditions.

Third, we illustrate the intricate relationship between possible "win-win" scenarios and the location choice of the reserve. In systems where there exists biological heterogeneity, closing the lower productivity area reduces the opportunity cost of the closure to fishermen while still providing positive biological benefits. In open-access fisheries, earlier evidence suggested that closing the most profitable patch would likely produce win-win situations. In a limited-entry fishery however, both the amount harvested and the net returns per unit of effort in the fishery determine whether aggregate license prices might increase. As a result, we find that closing the high cost area provides the most opportunity for a win-win result in a licensing limited-entry setting.

Finally, we find that getting the most out of reserves may call for additional policies. In particular, in many cases it may be necessary to reduce the limited-entry fleet by buy-back or other means to tailor the fleet to the new bioeconomic post-reserve conditions. Alternatively, regulators might consider implementing spatially-explicit instruments (e.g., area licensing) rather than spatially uniform instruments (e.g., fishery-wide licensing) in order to further optimize effort, catches, and biomass distribution.

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