

Reserve Site Selection in a Limited-Entry Fishery

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Abstract

Marine reserves are gaining attention around the world as a tool to both conserve ocean resources and improve the conditions of the fishing industry. Such a win-win outcome occurs when the dispersal benefits from the reserve are greater than the opportunity cost of closing the area to fishing. We investigate in a limited-entry setting the inherent bioeconomic trade-offs associated with reserve site selection—that is, the trade-offs between the degree of connectedness of a site and the biological and economic habitat heterogeneity. We find that choosing patches that have the greatest potential to provide spillover to other patches is not necessarily the best bioeconomic strategy. It is a good strategy when the bioeconomic system is homogeneous, but as the degree of bioeconomic heterogeneity increases, it is the bioeconomic habitat conditions combined with the nature of the linkages that are the critical drivers.

Key Words: fisheries; limited-entry; marine reserves; marine reserve networks

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James N. Sanchirico*

1. Introduction

President Clinton issued three executive orders regarding the stewardship and conservation of U.S. marine resources. The first order created the Coral Reef Task Force, whose mission is to strengthen the stewardship of the nation's coral reefs (Federal Register 1998). The task force recommended designating special areas, including "no-take zones, to protect and replenish coral reef ecosystems and prevent future harmful impacts" (Coral Reef Task Force 2000). The second and arguably more far-reaching effort came in 2000, when federal agencies were instructed to develop a national system of marine protected areas (MPAs) (Federal Register 2000). Also in 2000, the Clinton administration authorized an 84-million-acre MPA in the northwestern Hawaiian Islands, which encompasses nearly three-fourths of the coral reefs in U.S. waters (Federal Register 2000).

Those orders came after a decade-long movement within the marine conservation, fishery biology, and ecology communities calling for increasing the scale and scope of closed areas in the management of marine ecosystems. The movement culminated in 2001 when more than 160 marine scientists signed a Scientific Consensus Statement (2001) outlining the potential benefits of marine reserves. Some of the more prominent outcomes that proponents cite are increased biodiversity, additional sources of larvae and biomass, increased levels of biomass throughout the fishery, increased catches, and a hedge against management failures (Polacheck 1990; Dugan and Davis 1993; Roberts and Polunin 1991; Carr and Reed 1993; Roberts 1998; Lauck et al. 1998; Murray et al. 1999; Halpern 2003). Ancillary benefits include education, diving, photography, and tourism (Bohnsack 1993; Sobel 1993). All of these benefits are thought to lead to and enhance the long-run sustainability of fisheries.

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With proposals on closures ranging anywhere from 20% to 90% of the fishable habitat (Lauck et al. 1998), it is no surprise that the current users of the grounds that may be closed fear the immediate effects and the lost access to particular fishing grounds in the future. Those concerns have legitimacy, and given the diverse set of stakeholders in U.S. fishery policy, compromises over the location, size, and number of marine reserves are inevitable. Therefore, it seems expedient to search for cases that yield the greatest gain in the biological health of the system at the lowest cost to the fishing industry. In fact, most of the literature on marine reserves has assessed their effects on measures, such as increased fish populations and aggregate catches, that appeal to both conservationists and fishermen. Typically, reserves are found both theoretically and empirically to increase the biomass in the reserve (e.g., Halpern 2003), but whether the fishing industry directly benefits depends on whether the dispersal benefits (“spillover”) from the reserves are greater than the opportunity cost of closing the area to fishing.¹

In general, dispersal benefits are a function of the connectivity of the system, population levels in the reserve, and dispersal mechanisms and rates—all of which depend on the species the reserve is set up to protect.² For sedentary adults that are broadcast spawners, for example, the dispersal benefit is increased production of larvae. For species with mobile adult populations, the benefits depend on whether the adults disperse randomly or follow seasonal migration patterns. The distribution of the dispersal benefits also depends on dispersal rates and distances (Botsford et al. 2001). A typical assumption would be that larvae are uniformly distributed across all subpopulations in a system, or that adult connectivity is defined by a system where only the nearest neighboring areas are directly connected.

The opportunity costs are a function of the response of fishing effort and the bioeconomic conditions in the area prior to closure. The appropriate metric depends on the institutional setting where reserves are being contemplated, the time frame over which reserves are to be

¹ 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: Carr and Reed (1993); Farrow (1996); Thomson (1998); Allison et al. (1998); Guenette et al. (1998); National Research Council (2001); Botsford et al. (2003).

² The dispersal of larvae and adults (and juveniles) is complex and poorly understood, but there is optimism among marine scientists that improvements in genetic analysis, mark and recapture methods, otolith geochemistry, and oceanographic models of currents, gyres, and coastal upwelling processes will lead to a better understanding of these processes.

evaluated, and the nature of the stakeholders.³ Under open-access conditions, rents are not a good metric because they are dissipated both before and after reserve creation. There is, however, the potential for transitional quasi-rents (Holland and Brazee 1996; Sanchirico and Wilen 1996; Hannesson 1998; Pezzey et al. 2000). In this case, the present value of these quasi-rents might be a suitable measure of the opportunity costs of closing an area to fishing. Researchers have also focused on the equilibrium level of aggregate catch. When the fishery is characterized by more rationalized management—for example, licensed limited entry or individual quotas—there is the possibility that reserves could increase the overall rent. If postreserve rents increase, then under rational asset pricing theory, an appropriate metric would be the license or quota prices, which reflect the associated gains or losses in rents (Sanchirico and Wilen 2002a). Regardless of the metric, the net effect depends on how fishermen respond: whether they contract or expand their effort and where they focus their effort after the area is set aside.

The principal components of the dispersal benefits and opportunity costs have for the most part been derived using models that consider two patches in an open-access setting (e.g., Hannesson 1998; Pezzey et al. 2000; Sanchirico and Wilen 2001a).⁴ Although these models are sufficient to develop intuition regarding the impacts of marine reserves, policymakers charged with implementing the executive orders are operating in settings where there are numerous potential sites to consider (see, e.g., Leeworthy and Wiley 2000, 2002). An important question, therefore, is whether the results found in two-patch models hold when we consider the case of multiple patches. For example, in more realistic systems, there is the possibility that certain patches might be better sources of biomass than others. Allison et al. (1998) also propose that the greater the number of patches a patch is connected to, the greater the dispersal benefits—a proposition that can be tested only in a multiple-patch setting. Finally, the Clinton

³ Since most bioeconomic analyses consider only commercial fishing interests, we focus our attention on this sector. In a more general framework that includes other users (e.g., nonconsumptive users and recreational anglers), the metric could be a single unifying welfare measure.

⁴ Some exceptions are papers by Polacheck (1990) and Holland and Brazee (1996), who assume that total fishing effort is constant but fishing mortality in the closed area is simply transferred into the open area after reserve establishment, and Sanchirico and Wilen (2002a), who consider the impact of reserve creation on limited-entry fisheries in a three-patch simulation. This paper differs from the latter in that we consider reserve creation in a optimally managed limited-entry system in a more complex metapopulation structure based on nine patches. We also investigate the relationship between various reserve locations, habitat heterogeneity, and dispersal and connectivity.

administration's second executive order proposes a national system of MPAs or network of marine reserves (Murray et al. 1999). Understanding the bioeconomic effects of marine reserve networks requires a model that considers multiple patches where the patches are both economically and biologically connected.

The first contribution of this paper is to develop a simple, intuitive, spatially explicit bioeconomic model that can be used to analyze the impacts of reserve creation in a system with multiple patches. The model provides insights into whether the qualitative properties of the two-patch results found in the literature hold in multiple-patch settings, and how the location of the patch in the system can play an important role in determining the net effects of reserves. For example, do site selection rules based solely on a patch's characteristics go astray by not considering the bioeconomic conditions of the remaining fishable habitat, especially the patches that are connected to the reserve? This is an important question that is often overlooked in the biological literature on reserve site selection that focuses on finding biologically productive patches.⁵

The second contribution is to illustrate the potential trade-offs between economic and biological habitat heterogeneity on the one hand, and the number of patches connected to the reserve via dispersal on the other. This analysis could help fishery managers reduce the set of feasible sites and thus reduce transaction costs in the negotiation process. The current precedent for site selection, as developed in the creation of reserves in the Channel Islands off southern California and in the Tortugas off the Florida Keys, is that biologists propose a list of areas, and then the fishing industry and other groups propose areas more suitable to their needs. This iterative process has been successful in reaching agreements in these two settings, but no one would describe it as the path of least resistance (Schmidt 1997). But what if regulators could predict *ex ante* which sites would encounter the least resistance from the fishing industry and at the same time satisfy the stated biological goals—that is, which sites and which fisheries would most likely benefit all stakeholders?

Although detailed empirical bioeconomic analysis is needed to quantify the benefits and costs for any particular fishery (e.g., Holland 2000; Smith and Wilen 2003), policymakers will

⁵ Sala et al. (2002) develop a model for designing marine reserve networks that considers detailed ecological processes operating in each patch, such as spawning, recruitment, and larval connectivity. Although the authors discuss the importance of including socioeconomic processes in designing networks, their model includes only the level of fishing pressure in each area.

no doubt be required to predict the biological and economic benefits and costs of setting aside areas before such an analysis can be completed. Analysis that can simulate more fishery characteristics than can be done empirically can thus play an important role in the debate on which patch to close.⁶

The paper is organized as follows. In section 2, we develop a spatially explicit bioeconomic model of a commercial fishing fleet operating under a limited-entry regime that exploits different subpopulations of a metapopulation. The model depicts a limited-entry fishery because most important fisheries in developed countries worldwide are either subject to some kind of limited-entry regulation or likely to have such programs in the near future. In section 3, we analyze the effects of reserves on aggregate biomass, effort, and rents in a nine-patch setting. Section 4 concludes with a discussion of the findings of the paper and the need to couple effort-reduction policies, such as vessel buy-backs, with the establishment of marine reserves.

2. Bioeconomic Metapopulation Model

Most of the economics literature investigating marine reserves is built on the traditional view that a fishery comprises one large homogeneous habitat with a population that is perfectly mixed throughout.⁷ But fisheries consist of multiple patches of stocks that are interconnected and can have different roles in the sustainability of the population and returns to fishing effort. The importance of habitat quality and heterogeneity on persistence of populations has recently gained support among ecologists (Levin 1992), especially in the assessment of marine reserves (Garcia-Charton and Perez-Ruzafa 1999; Crowder et al. 2000). This has led, for example, to such questions as, What are the effects on the potential benefits and costs of setting aside areas of high biological productivity and high cost? The traditional view, however, does not provide any dimensions over which this question can be analyzed.

⁶ This analysis also highlights how varying costs, biological productivity, and the position of the patch in the connectivity of the system can drive results in empirical bioeconomic models—factors that can sometimes be difficult to disentangle in more complex settings.

⁷ These models investigate how different sizes of marine reserves affect such measures as spawning stock biomass, yield per recruit, catch levels, and stock and catch variability (Polacheck 1990; Holland and Brazee 1996; Hannesson 1998; Pezzey et al. 2000). By assuming that reserves are a fraction of the fishery, these models are discrete spatial approximations to a continuous space-time formulation. A typical assumption in these formulations is that the scale of the open and closed area is separable from the underlying biological and economic production functions—an assumption that is likely not to hold as the reserve size approaches zero and one.

Following Sanchirico and Wilen (2001a, 2002a), we construct a bioeconomic metapopulation model that treats space explicitly in the form of discrete patches. Using this framework, we illustrate how patch or habitat heterogeneity interacts with dispersal and connectivity to determine the nature of the bioeconomic trade-offs. Because we focus on the effects of marine reserves on equilibrium levels, we do not present the underlying dynamics that lead to such an equilibrium (see Sanchirico and Wilen 2001b for a presentation of the dynamics). The equilibrium solution, however, is consistent with a steady state derived from a more complex dynamic (optimal control) framework.

We depict a regulator who determines the total amount of effort (or licenses) in the fishery and which patches are open to fishing, such that fishery-wide rents (R) are maximized. Under the limited-entry system considered here, aggregate rents are equal to the product of the license price (L , rents per unit of effort) and the total effort operating in the system (E^{Tot}). The mixed-integer programming problem the regulator solves is

$$\begin{aligned}
 \max_{E^{Tot}, \gamma_i} \quad & R = L * E^{Tot} \\
 s.t. \quad & \gamma_i h_i(x_i, E_i) = f_i(x_i)x_i + d_{ii}x_i + \sum_{\substack{j=1 \\ j \neq i}}^{n_i} d_{ij}x_j \quad \forall i \in N \quad (1) \\
 & \gamma_i R_i(E_i, x_i, L) = 0 \quad \forall i \in N \quad (2) \\
 & E^{Tot} = \sum_{i=1}^N \gamma_i E_i \quad (3) \\
 & \gamma_i \in \{0, 1\} \quad \forall i \in N \quad (4)
 \end{aligned}$$

where γ_i is a 0/1 variable that is equal to 1 if the patch is open to fishing, and 0 if the patch is closed to fishing. The aggregate amount of effort (number of licenses) is modeled as a continuous variable. It is important to point out that the solution is an optimal second-best equilibrium. These are not first-best solutions because the regulator is determining not the optimal spatial distribution but only the total effort, which then redistributes to dissipate rents across the system. The first-best solution is when the regulator can control the level of fishing effort *in each patch*, as described in Sanchirico and Wilen (2002b).

Constraint (1) is the sustained biological equilibrium defined at the point where catch directly offsets biological growth and dispersal. The components of constraint (1) are defined as follows: 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 open/closed variable occurs in the constraint to indicate that when a patch is closed, it equilibrates at an unexploited biological equilibrium. We assume that the local growth function follows the logistic growth curve where the two lumped parameters are the carrying capacity (k_i) and the intrinsic growth rate (r_i). The biological system depicted here is a deviant of the 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. 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} , which can be interpreted as the dispersal of the fish population subject to fishing pressure.⁸ The set of patches biologically connected to any given patch is defined by n_i .

The equilibrium distribution of effort throughout the patches is determined by constraint (2), which states that net rents, including the license price, are dissipated in each patch.⁹ Rents in each patch are equal to $R(E_i, x_i, L) = p_i q_i E_i x_i - (c_i + \pi) E_i - \delta L E_i$ for all $i=1, \dots, n$ where the catch function is $h_i = q_i E_i x_i$ (q_i is the catchability coefficient), c_i is the constant patch-specific costs per unit effort, π is a common vessel capital opportunity cost, and δ is a discount rate, which converts the common license price into current value terms or an annualized license lease price.¹⁰

The simplest way to see that rents net the license lease price are dissipated in equilibrium is to note that a 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 present value of the anticipated production rents in the fishery. Then L is the amount that a potential entrant would be willing to pay an existing participant to purchase his or her vessel-

⁸ According to Carr and Reed (1993), models with larval dispersal processes are best suited to model marine reserve creation for fisheries where recruitment overfishing is occurring (i.e., the number of fish entering the harvestable stock is reduced by too much fishing on spawning stocks), and models of adult-juvenile dispersal process are better suited to investigate reserve creation in fisheries with growth overfishing (i.e., a reduction in the mean size of the harvestable individuals).

⁹ The behavior depicted in the model is consistent with regulated open-access settings where fishermen respond to regulations by increasing other uncontrolled factors of production until all quasi-rents generated by the policy are dissipated.

¹⁰ As it is currently modeled, the license price is equivalent to a charge per unit of effort. Of course, the model is also qualitatively equivalent to a model depicting an individual fishing quota system where quota rights are not area specific.

specific license. The (common) license price will be endogenously determined and is a function of the total number of licenses outstanding (E^{Tot}).

In equilibrium, the license 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 vessel capital will be indifferent between participating in the alternative fishery and earning π per unit capital, or participating in the limited-entry fishery by paying the price L and earning $p q_i x_i - (c_i + \pi)$ 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 price L will be indifferent between fishing in patch j and in patch i , so that $(1/\delta)(p q_i x_i - (c_i + \pi)) = L = (1/\delta)(p q_j x_j - (c_j + \pi))$.¹¹

The third constraint (3) depicts a fishery that is regulated by a limited-entry licensing system with licenses placed on vessels; it ensures that the amount of effort operating in the fishery is equal to the number of licenses.

Dispersal and Connectivity

We follow the long tradition in the ecology literature of depicting dispersal processes as dependent on relative densities.¹² That is, biomass flows from patches with high density to patches with lower density, everything else being equal. The simplest representation of a density-dependent dispersal process depicts the dispersal mechanism between patch 1 and patch 2 as $d_{11}x_1 + d_{12}x_2 \equiv b(x_2/k_2 - x_1/k_1)$, and between patch 2 and patch 1 as $d_{22}x_2 + d_{21}x_1 \equiv b(x_1/k_1 - x_2/k_2)$. To ensure that the amount of biomass that leaves one patch for another is equal to or less than the amount that enters the patch, we impose restrictions on the dispersal parameters. In particular, we impose the symmetry condition that $d_{ij} = d_{ji}$. The symmetry condition, along with $\sum_{k=1}^{n_i} d_{ki} = 0$ $i=1,2,\dots,n_i$, ensures that whatever leaves patch i for j also arrives in j specifically from i . If these restrictions are not imposed, models can predict that *more* biomass arrives in a patch than what left for the patch (e.g., Holland and Brazee 1996; Hannesson 1998). Although this is not likely to affect the

¹¹ This particularly simple structure is due to the rent function's being linear in E . This makes marginal rents equal to average rents, which simplifies the nature of the rent-dissipating relationships.

¹² The literature on reserves also discusses other formulations that depict unidirectional 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.

qualitative properties of the models, it can clearly affect the quantitative predictions regarding the benefits and costs of marine reserve creation.

In figure 1, we illustrate the integrated nine-patch biological system, where the arrows represent linkages between the patches. The system is characterized by varying degrees of connectedness, where the shape of the patches was chosen to maximize the heterogeneity in the number of linkages. For example, patch 3 is linked to two other patches, whereas patch 2 is linked only to 5, and patch 5 is linked only to 6. We consider nine patches because this is the smallest number that captures the broadest set of connections. More patches would just duplicate the general pattern illustrated. Thus, we use this simple nine-patch system to build intuition. Figure 1 also illustrates the elements of the sets n_i . In patch 1, for example, n_i consists of $\{2, 4\}$.

This metapopulation framework may be used to depict a wide variety of circumstances regarding both the behavioral characteristics of dispersal processes and the oceanographic features of a spatial setting. For example, the model can be used to describe a broadly homogeneous continental shelf area with many local microhabitats containing resources, where dispersal distances of some patches might be limited by currents, gyres, or geological features (e.g., a spit). Some patches may have higher biological productivity than others, and some, like larval pools that receive and disperse larvae from other patches, may have no inherent productivity. The framework therefore enables us to investigate in many different settings how the selection of sites for reserves can affect dispersal benefits and opportunity costs.

3. A Nine-Patch Equilibrium Analysis of Marine Reserves

The bioeconomic metapopulation system outlined here is particularly useful for examining the impacts of reserve formation and for examining the role of location choice in a heterogeneous fishery. It also allows us to conduct many more investigations into the role of various ecological and economic structures than can be done empirically. In addition, the model can be used to analyze other spatial instruments, such as gear restrictions and individual transferable quotas, and to compare these instruments with reserves.¹³

¹³ The limited-entry system considered here is a nonspatial policy where aggregate effort is controllable; a spatial limited-entry system would include licenses for each patch.

Most of the research on marine reserves has focused on finding conditions where aggregate catches and biomass increase. In a limited-entry fishery, we focus on aggregate rents, effort, and biomass. Fishery-wide rents and total effort are considered because reserves can potentially increase rents in the fishery, especially in a second-best setting. Furthermore, in many cases, marine reserves might need to be coupled with effort-reduction policies to realize the greatest economic gain.

We solve the regulator's problem for all possible reserve configurations, including multiple-patch closures, implying that there are 2^9 (512) possible reserve configurations. In more complicated systems or with more patches, the computational burden of such an approach would be too great and require the use of either branch-and-bound or heuristic algorithms.¹⁴

In all simulations, we find that the optimal second-best solution is to keep all patches *open* to fishing. This is consistent with Sanchirico and Wilen (2002a), who found that reserves increase rents in a limited-entry fishery only when total effort is near the open-access levels. There are, however, benefits of marine reserves beyond the fishing industry, implying that even if there are costs to the fishing industry, reserves might still be used as a management tool. For example, regulators might be interested in closing approximately 10% of the habitat for conservation of biodiversity. The question then becomes, What is the magnitude of the reductions in rents and total effort associated with closing a patch? Finding the site where the effects on the fishing industry are minimized will likely reduce opposition to creating a reserve.

We rank reserve configurations by fishery-wide rents, which we acknowledge are only one potential goal of marine reserves, for both closed and integrated biological systems. We report the closed case because the rankings map one-to-one each patch's contribution to overall fishery-wide rents. For example, if patch 2 is the highest-cost patch to operate in, then closing it will have the least effect on aggregate rents, and patch 2 would be the top-ranked case. In addition, the comparison between closed and integrated systems, where the differences are due to the spatial linkages, illustrates the role that linkages play in determining the relative contribution of each patch to overall fishery-wide rents. Of course, the rankings depend on the parameter levels in the system because the levels of patch biomass, effort, and rents change. The results are

¹⁴ The operational research and conservation biology literatures have studied extensively the terrestrial reserve site selection problem, paying particular attention to developing optimization and heuristic algorithms to solve these problems (e.g., Polasky et al. 2000; Haight et al. 2000)

therefore best viewed as illustrative of general processes rather than as indicators of the expected magnitude of the impacts from marine reserves.

For the integrated system, we also present percentage changes in aggregate rents, effort, and biomass from the case when all patches are open to fishing. These provide additional information on the relative differences and the potential trade-offs when creating reserves to meet multiple goals. It is important to point out that the magnitudes of the percentage changes depend on the absolute and relative parameter levels. For example, higher dispersal rates can lead to greater increases (decreases), everything else being equal.¹⁵

Although the optimization problem is solved for all 512 possible configurations, we present only the top 15 cases. This includes cases where multiple patches are closed, thereby providing information on potential optimal combinations of patch closures. Such information is important, for example, in analyzing the effects of marine reserve networks, and if marine scientists recommend that 20% of the habitat (two patches) needs to be closed to maintain a certain level of biodiversity.

We first present the case where both the biological and the economic habitats are homogeneous, but heterogeneity exists because of the varying degrees of linkages across the patches, as illustrated in figure 1. This case allows us to illustrate the effect of the different degrees of linkages. Next we consider the case where the biological system is homogeneous, but costs vary across the system. Then we focus on biological heterogeneity in a system where the cost of fishing is identical across the areas. Finally, we combine both economic and biological heterogeneity to illustrate that in a complex heterogeneous environment, simple rules might lead to adverse outcomes, even though patterns do evolve. In each scenario, we did extensive sensitivity analysis, but for expositional purposes, we present only one set of results. We discuss additional findings throughout the text.

¹⁵ In all simulations, we calibrate the dispersal rate such that the ratio of the dispersal rate and median growth rate is equal to .2. This level can be shown to maximize the dispersal benefits in a two-patch setting. The median growth rate is used to ensure interior solutions (nonnegative levels of effort and biomass). See Sanchirico and Wilen (2001a) for a discussion of the feasible set of the parameter space with respect to dispersal and growth rates. We also make the following scaling and simplifying assumptions: $k_i=1$, $q_i=q$, $p_i=p$ for all $i=1,\dots,N$.

Homogeneous Habitat

When the biological system is closed and homogeneous, there is no difference in aggregate rents, effort, or biomass when each of the nine patches is closed to fishing. Linkages and dispersal do create differences even in the homogeneous setting, however, and play an important role in determining the magnitude of the differences across the cases. Not surprisingly, we find in the integrated homogeneous system that closing patch 5 leads to the smallest reduction in rents. Patch 2 is not far behind. This result confirms the hypothesis of Allison et al.(1998). Patches with greater linkages will increase the dispersal benefits and provide the greatest opportunities for limiting the impacts on the fishing industry. However, at the same time, the increase in the aggregate biomass is lowest when patch 5 is closed. With more avenues for dispersal, the equilibrium biomass level is lower because growth is offset by net dispersal. Even though there is no biological and economic heterogeneity, we still find a bioeconomic trade-off between aggregate biomass increases and returns to fishing effort.

Heterogeneity in Costs

We consider the case where economic heterogeneity exists and is captured by differences in the cost parameters. To avoid assigning different cost parameters to each patch, we sample from a uniform distribution each of the nine cost parameters. In this example, patch 2 is the high-cost patch and also the patch with the second highest number of linkages in the system. Patch 5 is one of the lowest-cost patches, implying that closing it could greatly affect the profitability of the fishing fleet. The relative cost levels and linkages across the patches are illustrated in figure 2, case 1, where we plot the deviations from the median.

In table 1, we report the ranking of patch closures with respect to fishery-wide rents for both the closed and the integrated systems. It is important to point out that the solutions in the table are optimal second-best solutions subject to the constraint that a given patch (or patches) is closed. Given that patch 2 is the highest-cost patch and has the second highest number of linkages, we find that closing it has the least effect on aggregate rents in both systems. In the

integrated system, aggregate rents drop by 4%.¹⁶ Therefore, by closing patch 2, the regulator reduces the opportunity costs and increases the potential dispersal benefits. Patches 1 and 3 are next in terms of lower opportunity costs, but because they are on the edges of the system, we find that they are lower in the rankings than we would have predicted from our two-patch model or from the closed system. Patch 5, on the other hand, is second because of the greater dispersal benefits, even though it is one of the lower-cost patches, implying higher opportunity costs. This illustrates that in a multiple-patch setting, it is the combination of linkages and bioeconomic habitat characteristics that will determine the overall rankings.

We also find that the reduction in rents from closing one patch falls ranges from 4% to 9%, which is less than when two patches are simultaneously closed.¹⁷ What is interesting, however, about the multiple-closure case is that the top combination is not the combination of the top two individual patches, as it is in the closed system. This is because patches 2 and 5 are linked but patches 2 and 7 are not, implying that the spillover benefits are potentially higher when 2 and 7 are closed than when 2 and 5 are closed. Because patches 2 and 7 are not directly connected, there is less redundancy in the biological system (redundancy is when two reserve patches are directly connected and supply each other directly with biomass). In designing reserve networks, many contend that the reserves should be connected, but as the results illustrate, that might not be the best strategy if a regulator is concerned with the effects on the industry. However, there are other reasons for including redundancy as a design criterion for a marine reserve network—for example, as a risk management strategy to hedge against the collapse of a reserve population.

The small percentage increases of aggregate biomass in table 1 are striking. There are several reasons for this. First, we are comparing reserve creation with an optimal second-best solution in which the biomass levels are higher than maximum sustainable yield. Typically, researchers find much larger increases in aggregate biomass after a reserve is created because

¹⁶ Although we do not report changes in license prices, we found that license prices can fluctuate more widely than rents. For instance, when some patches are closed, the price goes down, and when others are closed, it increases. When the license price increases, the marginal vessel becomes more profitable, but because total effort is lower, aggregate rents have still decreased with the closure. The fact that license prices can go up or down is due to (1) this is an optimal second best setting; and (2) we are comparing discrete (not continuous) changes when patches are closed.

¹⁷ To put these figures in perspective, consider a hypothetical example. If a fishery's gross revenues are \$1 million and rents are 40% of the gross revenues, then a 10% reduction in aggregate rents corresponds to a reduction of \$40,000.

reserves are compared with open-access cases in which patches are overexploited (e.g., Hannesson 1998; Pezzey et al. 2000; Sanchirico and Wilen 2001a). Second, we find that the redistribution of effort after a reserve is created can reduce the levels of biomass in other patches. Therefore, the gains in the reserve can in some circumstances be offset by decreases in population levels in other patches.

Table 1 also illustrates that although a patch might be ranked at one level for rents, it could be lower or higher if a different objective is considered. For example, patch 7 has greater reductions in effort and lower increases in biomass than patch 6, but it is ranked higher in terms of rents. A more complicated, multiobjective analysis in which several criteria are jointly satisfied could be used to determine an optimal patch from a biological and economic standpoint. Although important, such a multiobjective analysis is beyond the scope of the current paper.

Closing off patch 2 will, of course, also affect the distribution of effort and biomass across the system. The spatial distributions of fishing effort and biomass are illustrated in figure 3, case 1. We find that effort increases in all patches in the system, but the greatest increases occur in patches that are linked to patch 2 and that were relatively unexploited before the reserve was created (i.e., high-cost areas). In these patches, spillover creates the greatest per unit increase in rents, and therefore the patches end up drawing greater levels of effort, everything else being equal. This is consistent with the observations that once areas are closed, fishing effort along the boundaries increases (McClanahan and Kaunda-Arara 1996). These findings illustrate the importance of understanding the biological linkages in predicting *ex ante* where fishing effort might focus after reserve establishment. Although some patches experience increases in effort, aggregate effort is still lower, as seen in table 1, because the increases do not outweigh the optimal reduction in effort required to maximize rents once an area is closed.

Heterogeneity in Growth Rates

Sanchirico and Wilen (2001a, 2002a) illustrate that closing off the most biologically productive patches, as measured by intrinsic growth rates, will not be the best strategy from the industry's perspective. That is, closing the most biologically productive patches increases the opportunity costs because patches with greater intrinsic growth rates are more economically productive, everything else being equal. Consistent with these previous findings, we find in case

2 that closing patch 9, which is the least productive patch, has the lowest effect on rents.¹⁸ The comparison between the top five reserve configurations in the closed and integrated systems illustrates the interplay between relative biological productivity and dispersal. For example, patch 5, which has the median growth rate, ranks above patches 2 and 3, both of which have growth rates lower than the median (see figure 2, case 2). Recall that patch 5 is the most connected in the system.

Figure 3, case 2 also illustrates the ripple effects of the closure through the system. Patches 5 and 6, which are directly connected to the reserve, experience the greatest increases in biomass and in effort as fishermen respond to dissipate any quasi-rents generated by the closure. The increase in biomass in patches 5 and 6 is not as high as might be predicted with models that ignore the endogenous response of fishing effort to changes in biomass levels. It is also interesting to note the second-order bioeconomic effects in the system. Patches 5 and 6 experience the first-order effects because they are directly connected to the reserve. The second-order effect comes from the increase in spillover biomass in patches 5 and 6, which in turn leads to greater spillover into the patches connected to them. These second-order (ripple) effects are illustrated in figure 3, where patch 2, which is connected to both 5 and 6, experiences the greatest increase in fishing effort relative to the other patches in the system.

The multiple-patch closure results are similar to case 1, where the top-ranked reserve configuration is not simply the combination of the two top-ranked single-patch closures. Patches 2 and 9 are not directly connected; therefore there is no redundancy, as when two contiguous reserve patches supply each other with biomass. Closure of patches 2 and 9, therefore, leads to higher rents than when two reserve patches are directly connected.

Heterogeneity in Costs and Growth Rates

In cases 3 and 4, we model heterogeneity in the cost and growth parameters. The patch parameter levels are again chosen randomly from a uniform distribution. In these cases, a patch can simultaneously be high-cost and high-productivity, making it difficult to predict whether the

¹⁸ Higher biological productivity in this setting occurs because some areas consistently have greater marginal productivity of production for all levels of population in all periods. This disparity could be due, for example, to unique oceanographic and geological conditions or to the presence of greater amounts of prey in one area than another. It does not capture spawning sites that hold large concentrations of fish only during certain times of the year.

dispersal benefits are likely to be greater than the opportunity costs. In these more complicated settings, the closed-system results provide important insights into how the combination of economic and biological heterogeneity translates into economic rents. For example, in case 3 (figure 3, panel 3), we find that the patch that contributes the least to rents is patch 4, which is the highest-cost patch. But the growth rate in patch 4 is above the median. The next lowest contributor to fishery rents is patch 9, which is the third highest in cost with a growth rate below the median. The third patch is patch 2, not patch 8, because the growth rate in 2 is lower than in 8 even though the costs in patch 8 are higher.

What are the effects of the linkages? Table 3 illustrates that the top-ranked patch is consistent across the closed and integrated systems, but after that there are differences depending on the number of linkages. Patch 2 is ranked second: although it is more profitable than patch 8, it has greater ecological value in the system because it has more linkages and thus more potential for spillover.

Although all single closures outscore the double closures in the closed system that is not the case in the integrated system. In this example, it is better in terms of fishery rents to close patches 2 and 4, which account for 22% of the habitat, than to close only patch 6, with 11% of the habitat. Two mechanisms appear to drive this result. First, dispersal processes can introduce nonlinear responses in the aggregate, analogous to lagged effects in dynamic analysis. Second, the relative bioeconomic conditions of the habitat could make certain patches top bioeconomic performers, with both low cost and high biological productivity. Closing such a “hotspot” could have larger negative effects than even closing two patches, especially if the two patches are high cost and low productivity. The latter mechanism is illustrated in case 4, which is discussed below.

Figure 3, case 3 illustrates the response of fishing effort to closing patch 4. Not surprisingly, we find that effort is drawn into the patches that are directly connected to the reserve. We also find that the optimal level of effort in the fishery is approximately 6% lower, implying that closing patch 4 will need to be accompanied by a buy-back of fishing licenses. The cost to society of closing patch 4 is the reduction in fishery-wide rents (3%). For the top ten choices, the range of costs in terms of reduction in fishery rents is 3% to approximately 10%. If a reserve is sited to conserve biodiversity, the reduction in fishery rents represents an estimate of the amount the public is willing to pay to conserve marine biodiversity. This estimate is readily available because the licensing limited-entry system considered here provides a price that captures the social value of the sustained exploitation of the fish population.

Case 4 is similar to case 3, and so we will not go into much detail except to point out that in this simulation, patch 5 is the top-ranked patch in the integrated system. Although patches 1 and 3 are less important to aggregate rents, patch 5 is closed because of its special role in the system. In the closed system, we also find evidence of bioeconomic hotspots, where multiple-patch closures are ranked higher than closing patch 2 and patch 8 (both of which are low cost and high productivity). Figure 3, case 4 also illustrates that effort increases as expected in all patches linked to patch 5 but decreases in patches 1 and 3, which are not directly connected to patch 5.

4. Discussion and Conclusions

The notable declines in New England groundfish and California rockfish stocks, along with claims that societies are mining the oceans in an unsustainable fashion, have prompted debate over how to restore or maintain healthy fisheries and ocean ecosystems. The growing momentum behind marine reserves as a management instrument follows directly from traditional policies focusing on reducing fishing mortality by controlling fishing operations. And although the use of area and time closures has a long history, the new approach focuses on providing protection beyond the spawning grounds and other areas identified as crucial to the life cycle of marine populations.

Unlike most of the economic literature on marine reserves, we analyze the effects of reserves in a limited-entry fishery where the regulator is choosing optimally the level of aggregate fishing effort and which patches to close to fishing. This is a second-best optimal because only aggregate fishing effort is controllable; the spatial location is determined by rent dissipation. Although the behavioral assumptions underlying the model are rather benign, the informational assumptions are substantial. In particular, the regulator is assumed to have perfect knowledge of the oceanographic processes, dispersal, and the bioeconomic habitat heterogeneity throughout the system. This is true, however, for all spatially explicit models developed to predict the effects of spatial management policies. Even without perfect knowledge, however, regulators could use this model to simulate many different cases. The analysis would provide a basis from which policymakers could better predict *ex ante* potential outcomes and then decipher *ex post* the factors that drove the results.

We find that the optimal second-best solution is to permit fishing in each patch. This result is consistent with the previous literature. Reserves can be used as a tool for more than fishery enhancement, however: they can ensure that special treasures, like unique habitat and biodiversity, are preserved for posterity. They also have the potential to provide a margin of

safety. Because reserves are placed within an exploited system, it seems prudent to develop tools that policymakers can use to determine the patches that are likely to encounter the least resistance from the fishing industry.

The multiple-patch analysis highlights the role that linkages play in determining the net effects of reserve creation—a point that is missed in a two-patch analysis. This includes not just the primary linkages between the reserve and its nearest neighbors, but also the secondary linkages between the patches connected to the reserve and the other patches in the system. The biological literature has focused on the biological effects of connectivity, which are illustrated here, but we also find that linkages are important for predicting the response of fishing effort. We also find that choosing patches that have the greatest potential to provide spillover to other patches is not necessarily the best bioeconomic strategy. It is a good strategy when the bioeconomic system is homogeneous. As the degree of bioeconomic heterogeneity increases in the system, however, it is the bioeconomic habitat conditions combined with the nature of the linkages that are the critical drivers.

Although the system is complex, patterns do emerge under the simplifying assumptions employed here. Patches that are low in productivity and/or high in cost are more likely to lower the opportunity costs associated with closing a particular patch, and therefore these patches are more likely to be acceptable to the fishing industry, everything else being equal. A significant determinant of the magnitude of the dispersal benefits is the bioeconomic characteristics of the neighboring patches. This implies that simple site selection rules based solely on a patch's bioeconomic characteristics might go astray by not considering the conditions of the remaining fishable habitat, especially the patches that are connected to the reserve. This important point is missed in most of the biological literature on reserve site selection, which focuses on finding patches that are inherently biologically productive. Of course, the relative and absolute magnitudes of the effects are particular to a fishery and will depend on bioeconomic habitat characteristics, dispersal process of the species, and oceanographic features of the system. Having said that, the analysis is built upon first principles, and therefore the fundamental properties and drivers illustrated are believed to hold in more general settings.

In some cases, we find that closing two patches lowers aggregate rents less than closing one patch—a discovery that necessitates the analysis of reserve creation in a multiple-patch setting. The result is due to the combination of bioeconomic hotspots—low-cost patches of high biological productivity—with high-cost and low-productivity areas, where the opportunity cost of closing a hotspot is greater than that of closing two of the least productive patches. Our findings also show that reserves need to be accompanied by effort-reduction policies in order to

realize the greatest economic gain. This result is consistent throughout all the simulations, with the range of effort reduction falling between 4% and 10% for the top-ranked reserve configuration and increasing thereafter. In general, the larger the habitat closed, the greater the number of licenses that need to be purchased, everything else being equal.

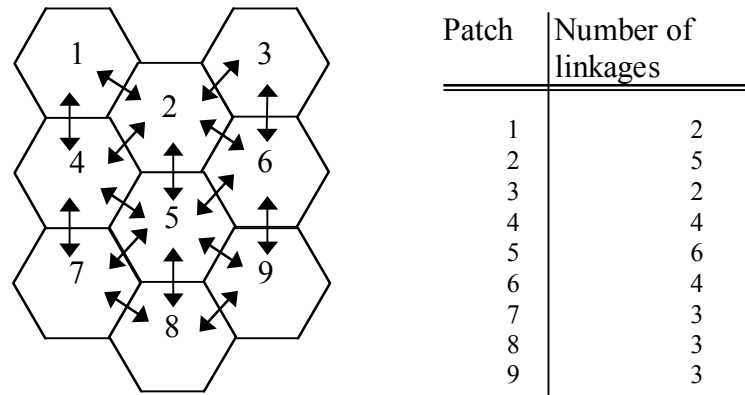
Given the current political economy of reserve creation, regulators might want to combine effort-reduction policies with closing off areas to fishing because industry might object less if it sees potential compensation for the lost fishing habitat. Compensation is provided to the exiting fishermen when their licenses are purchased (or through vessel buy-back programs). The remaining fishing effort is also indirectly compensated, since the returns per unit of fishing effort could be higher once the optimal number of licenses is retired. Without coupling reserve creation with policies that rationalize a fishery, any economic gains from a reserve will be dissipated as fishermen continue to operate under rule of capture incentives—the very circumstances that have created momentum for increasing the scale and scope of marine reserves.

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Figures**Figure 1: Nine-patch metapopulation system**

Note: The arrows represent the linkages.

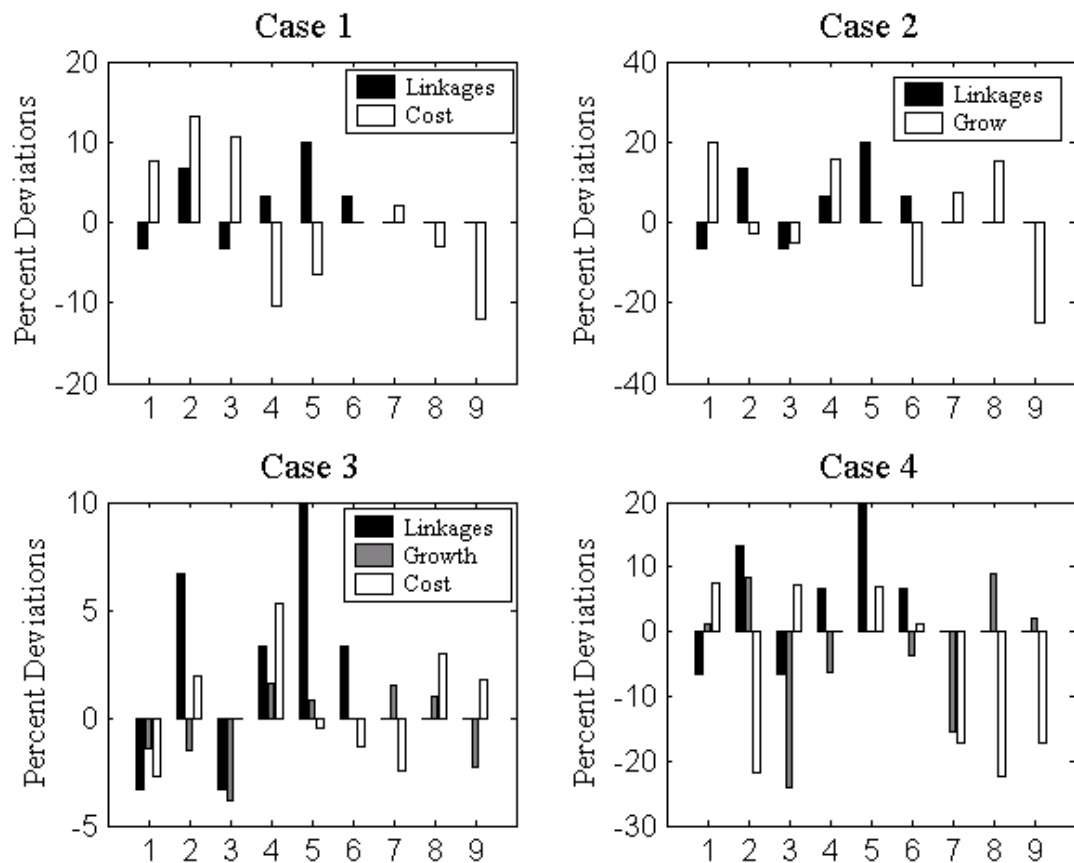


Figure 2: Biological and economic characteristics

Note: The percentage deviations are from the median (in some cases the deviations are scaled in order to show all levels on one graph). The numbers along the x-axis correspond to the patch numbers in figure 1. Case 1 considers only economic heterogeneity (cost levels) and case 2 considers biological only heterogeneity (growth rates). Cases 3 and 4 consider both biological and economic heterogeneity. The legend for case 4 is excluded, but the color mapping is identical to case 3.

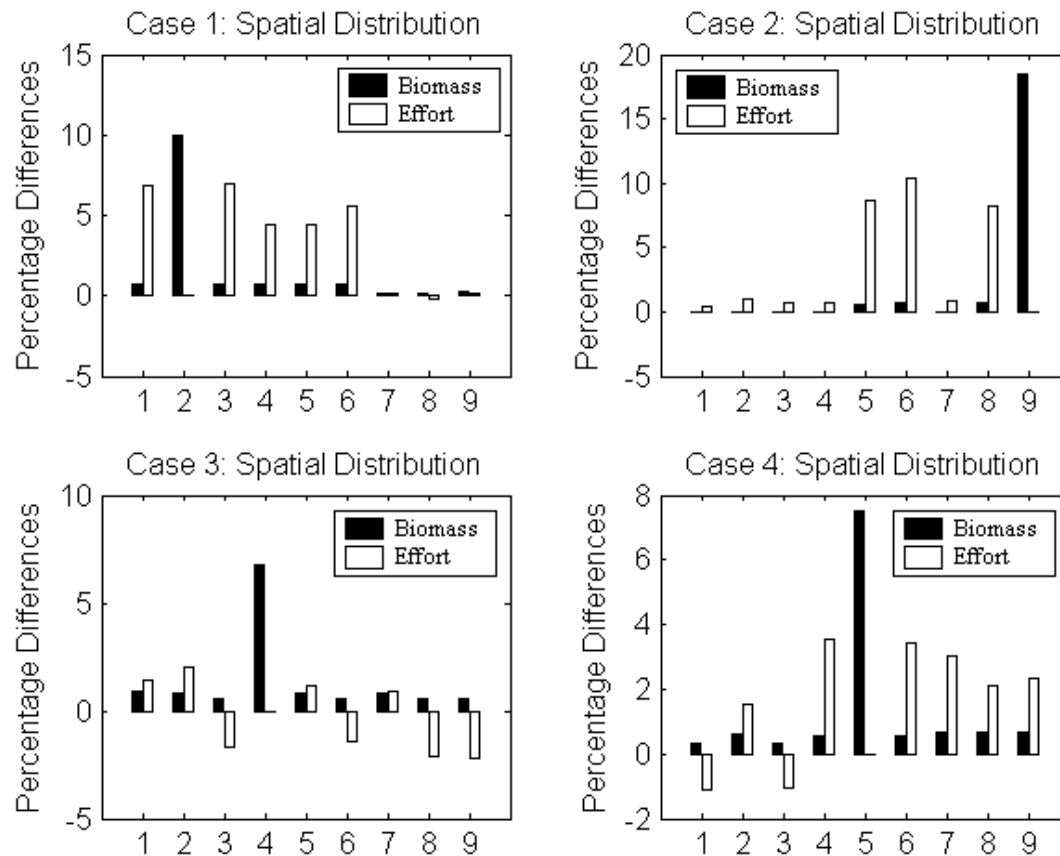


Figure 3: Spatial distributions of biomass and fishing effort postreserve creation

Note: The percentage differences are measured from the optimal case when all patches are open. The numbers along the x-axis correspond to the patch numbers illustrated in figure 1. The cases presented are for the top-ranked result, which is presented in the respective tables. The reserve patch is evident by the large percentage increase in biomass.

Tables

	<i>Closed system</i>	<i>Integrated system</i>			
<i>Rank</i>	<i>Patch closures</i>	<i>Patch closures</i>	<i>Aggregate rents</i>	<i>Aggregate effort</i>	<i>Aggregate biomass</i>
1	2	2	-4.29	-4.72	1.61
2	3	5	-6.60	-5.63	1.90
3	1	7	-6.66	-6.45	2.16
4	7	6	-6.74	-6.20	2.06
5	6	3	-6.83	-7.17	2.29
6	8	8	-7.10	-7.27	2.34
7	5	1	-7.45	-6.86	2.28
8	4	4	-8.49	-7.13	2.31
9	9	9	-8.96	-7.67	2.50
10	2,3	2,7	-11.08	-11.39	3.81
11	1,2	2,5	-11.82	-11.70	3.92
12	1,3	2,8	-11.85	-11.42	3.82
13	2,7	2,6	-12.15	-12.22	4.05
14	2,6	2,3	-12.36	-13.44	4.34
15	3,7	1,2	-12.67	-13.58	4.39

Table 1: Economic heterogeneity in an integrated system

Note: For the different reserve configurations, the percentage changes of rents, effort and biomass are from the case when all patches are open.

	<i>Closed system</i>	<i>Integrated system</i>			
<i>Rank</i>	<i>Patch closures</i>	<i>Patch closures</i>	<i>Aggregate rents</i>	<i>Aggregate effort</i>	<i>Aggregate biomass</i>
1	9	9	-6.03	-5.72	2.21
2	6	6	-6.15	-5.66	2.03
3	3	5	-6.36	-5.91	1.82
4	2	2	-6.66	-6.22	1.93
5	5	3	-8.19	-7.89	2.44
6	7	4	-8.48	-8.04	2.08
7	8	7	-8.59	-8.24	2.25
8	4	8	-8.94	-8.53	2.22
9	1	1	-10.29	-10.00	2.41
10	6,9	2,9	-12.81	-12.10	4.18
11	3,9	5,6	-13.52	-12.76	4.17
12	2,9	6,9	-13.53	-12.94	4.70
13	5,9	5,9	-13.65	-13.00	4.41
14	3,6	2,6	-13.94	-13.23	4.32
15	7,9	2,5	-14.04	-13.21	4.03

Table 2: Biological heterogeneity in an integrated system

Note: For the different reserve configurations, the percentage changes of rents, effort and biomass are from the case when all patches are open.

	<i>Closed system</i>	<i>Integrated system</i>			
<i>Rank</i>	<i>Patch closures</i>	<i>Patch closures</i>	<i>Aggregate rents</i>	<i>Aggregate effort</i>	<i>Aggregate biomass</i>
1	4	4	-3.13	-4.98	1.43
2	9	2	-4.83	-5.00	1.64
3	2	8	-5.91	-6.68	1.90
4	8	9	-6.07	-6.20	2.02
5	3	3	-7.46	-6.99	2.47
6	5	5	-7.78	-6.70	1.90
7	6	2,4	-8.68	-11.07	3.36
8	1	6	-8.87	-7.53	2.23
9	7	4,8	-9.07	-11.81	3.36
10	4,9	4,9	-9.23	-11.29	3.47
11	2,4	3,4	-10.67	-12.07	3.92
12	4,8	2,8	-10.79	-11.79	3.56
13	3,4	2,9	-11.00	-11.37	3.70
14	2,9	1	-11.60	-9.74	2.87
15	8,9	4,5	-11.83	-12.79	3.62

Table 3: Biological and economic heterogeneity in an integrated system

Note: For the different reserve configurations, the percentage changes of rents, effort and biomass are from the case when all patches are open.

	<i>Closed system</i>	<i>Integrated system</i>			
<i>Rank</i>	<i>Patch closures</i>	<i>Patch closures</i>	<i>Aggregate rents</i>	<i>Aggregate effort</i>	<i>Aggregate biomass</i>
1	3	5	−3.45	−4.48	1.35
2	1	3	−4.63	−5.53	1.93
3	5	6	−5.69	−6.01	1.80
4	6	4	−5.81	−6.01	1.83
5	4	1	−6.13	−7.32	2.03
6	7	3,5	−8.13	−10.12	3.30
7	9	7	−8.88	−7.60	2.50
8	1,3	1,5	−9.62	−11.93	3.40
9	3,5	5,6	−9.89	−11.50	3.42
10	3,6	4,5	−10.02	−11.52	3.45
11	3,4	3,4	−10.48	−11.65	3.78
12	2	9	−10.50	−9.04	2.45
13	8	1,3	−10.78	−12.94	3.97
14	1,5	3,6	−11.54	−13.15	4.17
15	1,6	2	−11.55	−9.15	2.27

Table 4: Biological and economic heterogeneity in an integrated system

Note: For the different reserve configurations, the percentage changes of rents, effort, and biomass are from the case when all patches are open.