



AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

Marine Reserves: Is There a Free Lunch?

James N. Sanchirico
James E. Wilen

Discussion Paper 99-09

December 1998



1616 P Street, NW
Washington, DC 20036
Telephone 202-328-5000
Fax 202-939-3460
Internet: <http://www.rff.org>

© 1998 Resources for the Future. All rights reserved.
No portion of this paper may be reproduced without
permission of the authors.

Discussion papers are research materials circulated by their
authors for purposes of information and discussion. They
have not undergone formal peer review or the editorial
treatment accorded RFF books and other publications.

Marine Reserves: Is There a Free Lunch?

James N. Sanchirico and James E. Wilen

Abstract

This paper employs a spatial and intertemporal model of renewable resource exploitation to investigate the effects of marine reserve creation. The model combines the H. S. Gordon/Vernon Smith hypothesis of a rent dissipation process with Ricardian notions that resources are exploited across space in a pattern dependent upon relative profitabilities. The metapopulation model employed here incorporates modern biological ideas that stress patch heterogeneity, linkages, and dispersal processes between patches. The spatial bioeconomic model is then used to simulate the effects of reserve creation under various ecological structures. We find, under certain parameter configurations and ecological linkages, that there is potential for a "double-dividend" where both aggregate biomass and harvest increase after an area of the fishery is set aside and protected from exploitation.

Key Words: marine reserves, spatial and intertemporal modeling, bioeconomics

JEL Classification Numbers: C62, Q22, R10

Table of Contents

| | |
|--|----|
| I. Introduction | 1 |
| II. A Bioeconomic Model of Spatial Exploitation | 2 |
| A. The Biological Model | 4 |
| B. A Model of Spatial Exploitation | 6 |
| III. Evaluation of the Impacts of Reserve Creation | 8 |
| A. The Closed System | 13 |
| B. Sink-Source Systems | 13 |
| C. Density Dependent Systems | 16 |
| IV. Discussion | 19 |
| References | 22 |

List of Tables and Figures

| | |
|--|----|
| Table 1. Pre-Reserve Bioeconomic Equilibria | 11 |
| Figure 1 Existence Conditions Two-Patch Density Dependent System | 12 |
| Figure 2 Double Dividend Conditions Sink-Source Case | 15 |
| Figure 3 Double Dividend Conditions Density-Dependent Case | 18 |

MARINE RESERVES: IS THERE A FREE LUNCH?

James N. Sanchirico and James E. Wilen*

I. INTRODUCTION

At the end of the nineteenth century the U.S. set aside several large land areas to preserve natural landscapes and areas of unique natural beauty in perpetuity. The establishment of these areas as national parks was by no means universally favored and was, in fact, surrounded by controversy. At the heart of the controversy were two opposing visions of functions natural areas might perform and the role users might play. One vision of man and nature, which originated in George Perkins Marsh's writings, saw man as an intruder and spoiler of natural areas. Believers in this view saw wild areas as sanctuaries in which natural systems could recover from the insults of mankind and perhaps attain their once unique level of pristineness. The other view arose out of the equally influential work of Gifford Pinchot, a German-trained forester who was an active policy maker in Theodore Roosevelt's administration. Pinchot saw natural areas as potential cornucopias of direct benefits to multiple users, the services of which could be optimized by wise stewardship and careful husbandry.

Over the past decade a similar movement has arisen in support of the idea of marine reserves or refugia. Like terrestrial reserves, the concept behind marine reserves is to set aside significant areas of the marine environment for limited or controlled use. Similar controversy has also arisen over how man and these marine environments ought to mix. On the one hand, some proponents see marine reserves as unique natural laboratories to be utilized as benchmarks and objects of study in order to understand relatively undisturbed natural systems. On the other hand, some see marine reserves as potential policy tools with which to enhance the benefits of coastal ecosystems generally (Davis 1989). For example, many proposals have focused on marine reserves as nursery grounds or larval protection areas which might enhance fishery production in adjacent fisheries (Roberts and Polunin 1991; Dugan and Davis 1993). In an important sense, then, the debate over marine reserves echoes similar debates that took place nearly a century ago over parklands and natural terrestrial areas.

* The authors are, respectively, Fellow, Quality of the Environment Division, Resources for the Future, and Professor, Department of Agricultural and Resource Economics, University of California, Davis. We thank participants at the European Association of Environmental and Resource Economists meeting (Lisbon, 1996) and the American Association of Agricultural Economists meeting (Toronto, 1997), and at seminars at UC Davis, Oregon State, Resources for the Future, and North Carolina State for helpful comments. This research was partially funded by a grant from the National Sea Grant College Program, NOAA, U.S. Dept. of Commerce, under grant number NA36RG0537, project number 89-F-N; and by the Division of Agricultural and Natural Resources and the Giannini Foundation, University of California. Address all correspondence to: James N. Sanchirico, email: sanchirico@rff.org

Ecologists and conservation biologists have written enthusiastically about the many ecological benefits that might emerge from marine reserves.¹ Some quite clearly view these areas as sanctuaries in the same vein that Marsh's followers suggested to justify terrestrial reserves. One enthusiast writes, "the concept of marine reserves is simple: If protected from human interference, nature will take care of itself." The often unsubstantiated implication is that a protected area will be more biologically diverse, more stable, and contain larger biomass levels and wider age distributions of species otherwise under threat. Others tout nonconsumptive benefits that come into conflict with fisheries exploitation, such as education, diving, photography, tourism, etc (Bohnsack 1993). Not surprisingly, some of the more vocal supporters are marine scientists who wish to work in relatively undisturbed environments.

The more vocal opponents of marine reserves are most often fishermen, who have mobilized with the vociferousness of the "not in my backyard" opposition to siting of hazardous waste sites. This may not be surprising when it is noted that the scale of some of the proposals for marine reserves is truly significant; recent proposals off California and Florida call for setting aside up to 30 percent of the marine habitat as protected area. Whether valid from a legal point of view or not, fishermen view reserves of this scale as a potential "takings" action, similar to other arenas in which government institutions expropriate "property." One conclusion to draw from much of this is that it will probably be politically important to have current users buy into attempts to establish marine reserves. Politically feasible reserve siting may, in the end, depend less upon purely biological considerations and more on obtaining tacit approval by fishermen, implying, in turn, that economic factors will play an important role.

This paper poses the predictive question: if we begin with an exploited system, what impacts will the establishment of a reserve have on the existing harvesters? What impacts will a reserve have on the health of the biological system? Under what circumstances does a marine reserve have the potential to provide most benefits (or smallest costs) to an existing fishery? We seek, in particular, circumstances in which closing an area currently open to harvesting actually makes both opponents and proponents of reserves better off. In the next section a simple bioeconomic model involving exploitation over space is laid out. In the third section, we use the model to analyze the implications of closing areas and establishing reserves. The final section discusses the results and summarizes.

II. A BIOECONOMIC MODEL OF SPATIAL EXPLOITATION

A serious exploration of reserve design issues should incorporate key ecological concepts such as patch dynamics, metapopulation models, dispersal processes, and heterogeneity across the spatial domain. These contemporary ideas focus on the role of **space**

¹ See Davis (1989); Polacheck (1990); Dugan and Davis (1993); Botsford et al. (1993); Quinn et al. (1993); Roberts and Polunin (1991); Mann, Law and Polunin (1995); Carr and Reed (1993); Allison, Lubchenco, and Carr (1998); Lauck, Clark, Mangel and Munro (1998).

in biological systems and the manner in which space affects fundamental processes. Not coincidentally, these are core intellectual concepts from the relatively new field of conservation biology, a field which itself has begun to emerge out of trying to understand issues raised by reserve creation in terrestrial settings. These concepts are being used to address issues such as whether it is best to have a single large or several small reserves, how corridors, edges, and patch configurations affect species viability and diversity, how viable population sizes are maintained via spatial dispersal, etc.

Since establishing marine reserves is generally most contentious in an exploited system, a robust model ought to incorporate a reasonable representation of a harvesting system as well as the biological system. Ideally, the harvesting sector model ought to incorporate sensible behavioral assumptions as well as realistic depictions of the institutional setting within which harvesting typically takes place. In most early discussions of marine reserves, the harvesting sector has been treated superficially. For example, some biological models of marine reserves assume that fishing mortality is constant before and after reserves, an assumption clearly unlikely if reserve creation alters economic incentives (Mann et al. 1995; Carr and Reed 1993). Others assume that fishing effort is constant but fishing mortality in the closed area is simply transferred into the open area after reserve establishment (Polacheck 1990; Holland and Brazee 1996). This is a step better than ignoring behavioral responses, but it only makes sense under limited entry programs with rents high enough to support the new higher effort level in the open area.

The model developed in this paper embeds several features which seem necessary to addressing the more important reserve design issues. First, while it is continuous in time, it is discrete over space. This discreteness is an important feature in our mind. Most other models developed to explore reserves consider the problem of carving out a fraction of space in an otherwise homogeneous system in which mixing is perfect, uniform, and (generally) instantaneous.² But while this is convenient analytically, it ignores much of the recent work in ecology that stresses patchiness, heterogeneity across space, and dispersal processes and linkages between patches.³ Ideally, if the policy issue were one of deciding which patches to select, it would be important to know which characteristics from among a spectrum of choices to focus on. Would it be better to pick areas with high intrinsic growth rates? High dispersal rates? Large number of linkages? Or, would it be wise to focus on high cost areas? Or low catchability areas? These issues cannot be readily addressed in analytical models that homogenize away important bioeconomic differences between patches. Second, our approach incorporates a richer depiction of the harvesting sector by embedding behavioral assumptions that motivate choice over space as well as over time. In particular, we assume that fishermen

² See Polacheck (1990); Mann, Law and Polunin (1995); Holland and Brazee (1996); Lauck et al. (1998); Hannesson (1998).

³ See, for example, Levin (1974, 1976); Roughgarden (1974); Hastings (1982, 1983); Vance (1984); Holt (1985); Roughgarden and Iwasa (1986); Possingham and Roughgarden (1986); Hastings and Harrison (1994). In addition, these ideas have not appeared in the natural resource economic literature with the exception of Brown and Roughgarden (1997) who examine the public good nature of larval pools in a metapopulation model.

respond to profit opportunities both by entering and exiting the fishery and by moving over space in response to spatial arbitrage opportunities. Consequently, the bioeconomic system is fully integrated over time and space, a feature which leads to the conclusion that reserve design is a joint economic and biological problem.

A. The Biological Model

We begin with a metapopulation model, where there are n discrete patches in space, each of which is characterized by "own" patch dynamics as well as linkages to other patches. Following Levin (1974, 1976), Hastings (1982, 1983), and others⁴, let the own rate of change of biomass in patch i be given by:

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

where x_i is the biomass level in patch i , $f_i(x_i)$ is the per capita growth 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 . In this formulation, own growth is separable from dispersal and the dispersal process is capable of depicting several different kinds of systems via appropriate choice of the coefficients d_{ij} . The ecological literature typically depicts dispersal processes as either **density dependent** or **uni-directional**. Density dependent dispersal processes have biomass flowing between patches in a manner dependent upon relative densities. The simplest type of representation of a density dependent dispersal process would be one in which the dispersal mechanism between patch one and two is $d_{11}x_1 + d_{12}x_2 \equiv b(x_2/k_2 - x_1/k_1)$ and between patch two and one is $d_{22}x_2 + d_{21}x_1 \equiv b(x_1/k_1 - x_2/k_2)$.⁵ In this simplest of cases, there is a common dispersal parameter b , and population biomass flows between patches in a manner dependent upon patch densities relative to natural carrying capacities. Note that, in this system, dispersal across space plays a role that augments own growth processes; when populations are low relative to carrying capacities, both own growth and dispersal from other patches operate in a complimentary fashion to bring populations to their carrying capacities at a faster rate. Note also that this system also has a directional gradient at each point in time that is endogenous, so that biomass flows to areas of low relative densities. When there is no exploitation in this system, the system approaches a **homogeneous** equilibrium in which all populations approach their respective carrying capacities. The equilibrium is homogeneous in the sense that there is no change in population levels in each patch and there is no dispersal across space, since relative densities are equal in equilibrium.

⁴ See, for example, Vance (1984) and Holt (1985).

⁵ This type of dispersal process is employed in papers by Huffaker, Bhat and Lenhart (1992), and Bhat, Huffaker, and Lenhart (1993, 1996) examining spatial/intertemporal control of a pest population, and in papers by Skonhofs and Solstad (1996) and Schulz and Skonhofs (1996) analyzing exploitation of transboundary terrestrial species.

Although much of the analytical ecology literature focuses on density dependent dispersal processes, there have been other formulations that depict uni-directional flow, often referred to as sink-source processes (Pulliam 1988; Tuck and Possingham 1994; Sanchirico and Wilen 1996). This subclass of models characterizes dispersal flowing from sources to sink patches regardless of population densities in the sinks. For example, a two patch sink-source model might have growth in the source patch equal to $r_1x_1(1-x_1/k_1)-b(x_1/k_1)$ and growth in the sink patch equal to $r_2x_2(1-x_2/k_2)+b(x_1/k_1)$. This type of dispersal process generates qualitatively different behavior compared with the density dependent formulation, mainly because biomass continues to flow between patches even after each population has reached its natural equilibrium. The unexploited equilibrium in this type of system will be a **non-homogeneous** equilibrium because even though patch population sizes are constant, they are maintained by continuous flows across space. In equilibrium, the source patch population will be maintained with positive net growth being balanced by emigration, and in the sink patch, negative net growth will be augmented by immigration.

The metapopulation model is thus capable of depicting a wide variety of circumstances reflecting both behavioral characteristics of a population and also oceanographic features of a spatial setting. We can stack the individual equations from (1) above into a system of unexploited individual patch growth equations as follows:

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x})\mathbf{x} + \mathbf{D}\mathbf{x} \quad (2)$$

where $\dot{\mathbf{x}}$ and \mathbf{x} are $n \times 1$ vectors, $\mathbf{F}(\mathbf{x})$ is a $n \times n$ diagonal matrix ($F_{ii}=f_i(x_i)$ for all $i=1, \dots, n$), and \mathbf{D} is an $n \times n$ matrix. The dispersal matrix \mathbf{D} captures the kind of dispersal process (density dependent or sink-source) as well as the spatial configuration of patches.⁶ For example, if the matrix has full rank, the implication is that each patch is connected to every other patch via dispersal, as might be the case in a broadly homogeneous continental shelf area with many local micro-habitats containing resources. On the other hand, one might wish to examine a coastal upwelling system within a narrow band of substrate in which the patches are adjacent so that each is linked via dispersal to neighboring patches only. In this case the \mathbf{D} matrix would be band diagonal. A sink-source system with a single source and multiple sinks would be represented with entries only in the column representing the source. Note too that one can capture a range of heterogeneous circumstances with respect to a system of individual patches.⁷ Some patches may have high biological productivity compared with others,

⁶ Ecologists generally impose some structure on the dispersal process, either to ensure sensible interpretation or for analytical convenience. In this paper we will impose the following restrictions on the \mathbf{D} matrix: (i) $d_{ii}<0$, (ii) $d_{ij}>0$, and (iii) $\sum_{k=1}^n d_{ki} = 0 \quad i = 1, 2, \dots, n$. Assumptions (i) and (ii) are accounting restrictions and (iii) is an "adding up" restriction which ensures that whatever leaves a patch during dispersal shows up in the receptor patches.

⁷ For a more detailed description of the possible formulations see, for example, Carr and Reed (1993); Allison et al. (1998), and Sanchirico and Wilen (1999).

whereas some may have no inherent productivity, as would be the case with a larval pool that receives and disperses larvae from a number of other patches.

B. A Model of Spatial Exploitation

To complete the bioeconomic model, we need to add a model of an exploiting industry. As discussed above, a sensible model of an industry ought to be explicitly spatial and behavioral, so that the fleet responds to economic variables over both time and space. The model we develop is a generalization of work by H.S. Gordon (1954) and Vernon Smith (1968, 1969). Both depict fishermen operating under open access conditions, responding to profits by entering until net rents are driven to zero. Consider first a model of exploitation of a single patch. Assume a composite effort variable E (which we can think of as vessels for simplicity), a population biomass level in the patch of x , and output price p . Then total industry revenues can be written $pH(E,x)$ where H is the industry production function. Consider similarly an industry operating cost function $C(E,x)$ and assume that each vessel has an opportunity cost π associated with alternative earnings potential outside the fishery in question. Then we can write average net rents per vessel as $R(E,x)=[pH(E,x)-C(E,x)-\pi E]/E$. Gordon hypothesized that as long as these net rents per vessel were positive, effort would enter the fishery, stopping only when average revenues equaled average costs, including the average opportunity cost. Smith generalized the Gordon model into a variant of a predator prey model, depicting the dynamic process by which vessels would enter and exit as proportional to these average rents, so that the bioeconomic system would evolve according to:

$$\begin{aligned}\dot{x} &= F(x) - H(E, x) \\ \dot{E} &= s[R(E, x)]\end{aligned}\tag{3}$$

In the Smith model (which nests the Gordon model), entry occurs when average rents per vessel are positive and exit occurs when rents are negative. The fleet interacts with the biomass and biomass rises or falls depending upon whether the harvest level can be sustained by biological growth or not. This system may approach the equilibrium asymptotically or in an oscillatory fashion, depending in part on the relative reaction speed of vessels to profits.

It is relatively straightforward to generalize the Gordon/Smith open access model to consider movement over space as well as entry/exit from an outside pool. This can be done by adding a spatial dispersal component to the Smith model above, in a manner similar to the metapopulation depiction of biological dispersal. Let E_i and x_i denote the patch specific levels of effort and biomass respectively in each patch i and let $R_i(E_i, x_i)$ be corresponding rents in patch i . Then we can hypothesize that the level of effort, E_i in patch i , will change according to:

$$\dot{E}_i = s_i R_i(E_i, x_i) + \sum_{\substack{j=1 \\ j \neq i}}^n s_{ij} [R_i(E_i, x_i) - R_j(E_j, x_j)] \quad , \quad i=1, \dots, n\tag{4}$$

In this specification, effort in patch i changes in response to two fundamental forces. The first is the level of rents *vis-a-vis* outside opportunities, captured in the first term. When patch i is earning positive rents so that net revenues exceed the opportunity cost of vessels, entry occurs into the system from the outside pool of potential effort.⁸ In this system, own patch responsiveness is determined by the rate parameter s_i . The second fundamental force operating on each patch may be called 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. 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 and in a manner that, in the long run, equalizes net rents across all patches. This will not be the optimum 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.

In a manner similar to the biological system, we can stack equation (4) for all n patches, and combine that matrix with the biological system to get:

$$\begin{aligned}\dot{\mathbf{E}} &= \mathbf{SR}(\mathbf{E}, \mathbf{x}) \\ \dot{\mathbf{x}} &= \mathbf{F}(\mathbf{x})\mathbf{x} + \mathbf{D}\mathbf{x} - \mathbf{H}(\mathbf{E}, \mathbf{x})\end{aligned}\tag{5}$$

Here $\dot{\mathbf{E}}$ and $\mathbf{R}(\mathbf{E}, \mathbf{x})$ are $n \times 1$ vectors, \mathbf{S} is an $n \times n$ matrix⁹ and \mathbf{H} is a vector of harvest rates dependent upon both biomass and effort. This depicts a spatially explicit biological system that is exploited by a harvesting industry responsive to rents within the system *vis-a-vis* both outside opportunities and opportunities across space. Again, this system is capable of modeling a variety of biological circumstances and a range of economic circumstances as well. For example, the economic dispersal matrix would be of full rank if vessels were free to move between any combinations of patches, or it might have zero entries if physical or institutional barriers prevented movement between subsets of patches (i.e. $s_{ik}=s_{ki}=0$).

While the above spatial and intertemporal bioeconomic system is capable of addressing a range of questions, it is particularly useful for examining the formation of reserves. 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 nature of the adjustment process to that exploited equilibrium.

⁸ The total effort operating in the fishery changes from one period to the next as a function of the net rents throughout the system ($\dot{E}^{total} = \sum_{i=1}^n \dot{E}_i = \sum_{i=1}^n s_i R(x_i, E_i)$).

⁹ The elements of \mathbf{S} are: $S_{ii} = s_i + \sum_{j=1, j \neq i}^n s_{ij}$, and $S_{ij} = -s_{ij}$ for $i, j=1, \dots, n$ with i not equal to j .

In this (pre-reserve) equilibrium, the level of own biological growth in each patch will be exactly offset by 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 equilibrium can be formally written as:

$$\begin{aligned}\dot{\mathbf{x}}^{set} = 0 &\Rightarrow [\mathbf{F}(\mathbf{x}) + \mathbf{D}]\mathbf{x} - \mathbf{H}(\mathbf{E}, \mathbf{x}) = 0 \\ \dot{\mathbf{E}}^{set} = 0 &\Rightarrow \mathbf{SR}(\mathbf{E}, \mathbf{x}) = 0\end{aligned}\tag{6}$$

Note that while the matrix of biological dispersal coefficients affects the equilibrium vector of biomass and effort levels in each patch, the matrix of economic response parameters only affects 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. Note also that the bioeconomic equilibrium is generally a **non-homogeneous** equilibrium, at least within the biological component of the system. In equilibrium, although the biomass levels in each patch are constant, the levels in each patch will be maintained in part by biological dispersal. Hence in a spatial and intertemporal equilibrium, there will be some biomass movement across space so that patch biomass levels are held fixed with some flow into the patch matched by an equal flow out of the patch. Note finally that the equilibrium in the whole system is, in general, fully integrated and simultaneous so that the equilibrium levels of biomass and effort in each patch depend upon biological and economic parameters (except response rates) in all other patches. In addition, the character of the equilibrium depends importantly on the structure of the biological dispersal matrix **D**.

III. EVALUATION OF THE IMPACTS OF RESERVE CREATION

In this section, we use the model outlined above as a point of departure for examining the implications of reserve creation. In principle, examining the **predictive** implications of reserve creation with this model is straightforward; once the base case of an exploited equilibrium has been examined and characterized, we can then simulate the implementation of a reserve system and compare. With the establishment of a reserve system, areas that were previously exploited would be closed to harvesting, with the initial effect that biomass in the reserves would grow. As biomass in the closed areas grows, density differentials between patches would be generated, potentially causing new patterns of biomass dispersal into the open areas. But dispersal of biomass would, in turn, generate new patterns of relative rents over space, leading to realignment of effort. In the long run, a new equilibrium distribution of biomass, effort, and harvest would emerge, and one could directly compare pre-reserve and post-reserve equilibria.

While it is reasonably straightforward to see how we might trace through the predictive implications of reserve creation, it is less clear how we should evaluate the **normative** implications.

For example, since this is an open access model, aggregate rents will be dissipated both before and after reserve creation and hence the conventional welfare implications are blurred.¹⁰ At the same time, issues arise about how to evaluate the biological implications. What is gained, after all, by setting aside no-harvesting zones? And, is it better to have more aggregate biomass, or should we pay attention to its spatial distribution as well?

We take a simple political economy approach here which sweeps aside most of these (difficult) welfare efficiency and other normative questions about reserve formation and optimal reserve policy. Instead, we return to the issues raised in the opening paragraphs by focusing on two questions. First, will reserves increase aggregate system-wide biomass? Second, can reserves increase aggregate harvests? Our interest in the aggregate biomass criterion stems from the belief that most biologists, managers, and regulators are mostly concerned about stock safety. That is, the worst outcome possible from mismanagement is, in their eyes, stock collapse and hence they are interested in ensuring that biomass is maintained at a reasonably high level. If managers are interested in system "safety," then it would be sensible to judge any increase in aggregate biomass due to reserve formation as a good policy. Our reading of the management science literature suggests that this is the most important motivation behind their recent support of marine reserves as a management instrument.¹¹ Aggregate (rather than patch-specific) biomass is a reasonable criterion because in a metapopulation system, individual patches may be driven to low levels and the system will maintain itself as long as other patches can disperse biomass into the low-density patches. It is even possible, in fact, to temporarily extinguish the population in a given patch in a metapopulation system, because other linked patches will replenish the patch via dispersal. In what follows we will assume that the main biological goal is one of maintaining a high system level of biomass.

How might an open access industry view reserve creation? We again adopt a political economy perspective and assume that the industry is interested in aggregate harvest. This seems sensible since we are beginning with an exploited system. Under these initial conditions, any patch closures that reduced aggregate harvests would likely be regarded unfavorably. Indeed the most vociferous objections to reserves seem to stem from the belief of fishermen that they are bearing the costs, in reduced harvest opportunity, from policies of otherwise questionable benefits.¹² But how likely is it that reserve formation might ever

¹⁰ This is also a result of assuming fleet homogeneity and a simple output market for the commodity. If, for example, we relaxed the assumption of fleet homogeneity we could calculate infra-marginal welfare effects from the resulting restructuring of the participants after reserves are created. In addition, we could also calculate the welfare implications of a more complex market structure for the harvesting sector. For example, if harvests go down and prices rise then reserve creation causes changes in consumer surplus.

¹¹ This is illustrated by the recent special issue of *Ecological Applications* devoted to sustainable management of fisheries (Feb. 1998) and in particular see the articles by Lauck et al. (1998) and Allison et al. (1998).

¹² While we realize that economists will certainly question whether a reserve that increases aggregate harvests ought to be judged as welfare improving (especially since rents are zero before and after reserves), we must emphasize that we are not evaluating reserves from a welfare theoretic perspective. Instead we are asking the question: When is it likely, in a political arena, that both proponents of reserves (mainly biologists and managers) and natural opponents of reserves (fishermen) might find themselves in agreement that reserve formation is desirable?

increase aggregate harvests? As we show below, there are circumstances when both biomass and harvests can increase with reserve formation. The likelihood depends upon whether the losses from closure are compensated by increased production in the remaining areas. Compensation, in turn, is possible if the closed areas disperse biomass to the remaining open areas, and if subsequent behavior by the industry does not dissipate all of those gains through excessive entry and harvest. As we demonstrate, it is possible to envision plausible circumstances in which reserve creation might be a policy option favorable to both managers and the industry. In these circumstances, setting aside areas from harvest creates a bioeconomic "double dividend" in the sense that aggregate system biomass levels (a proxy for stock safety) increase, and total harvest increases after closing one or a group of areas.¹³

In what follows we use a simple example with two patches to show how closing one patch affects several aggregate variables of potential interest. Fortunately, a two-patch system is sufficient to characterize the qualitative implications of reserve formation under most settings. We begin by assuming that both patches can be characterized by logistic own biological growth processes, $\dot{x}_i = f(x_i) = r_i(1 - x_i/k_i)$ with possibly different intrinsic growth rates r_i and carrying capacities k_i (with $i=1,2$). Now normalize by defining $X_i \equiv x_i/k_i$ so that instead of measuring biomass abundance, we measure biomass **density** in each patch. We leave the dispersal process unspecified for the moment, since we will examine a range of processes including density dependent and uni-directional. Although we could assume a variety of forms for the production function and cost function, as it turns out it is analytically convenient to assume that the production function is a Schaefer function so that $h_i = q_i E_i X_i$ and the cost function is linear in effort so that $C(E_i) = c_i E_i$. These assumptions are convenient analytically because they allow the system to be solved recursively. To see this, note that with these specifications, the rent equations are separable so that $R(E_i, X_i) = R(X_i) E_i$, where $R(X_i) = p_i q_i X_i - (c_i + \pi)$. With separability, rents are dissipated in each patch when the equilibrium levels of biomass densities are $X_i = w_i \equiv [(c_i + \pi) / p_i q_i]$. The equilibrium biomass densities are functions of the production function and cost function parameters as well as the (assumed common) opportunity cost π . Once the X_i 's are determined, they can be plugged into the respective equations (equations 6)) describing biological equilibria in each patch to determine the corresponding equilibrium effort level, as shown in Table 1.

Table 1 shows equilibrium levels of biomass density, effort, and harvest in each of two patches in several different types of two-patch systems before a reserve is established. In each case, the rent dissipation density levels of biomass are first determined as described above, so that biomass equilibrates with harvesting at a rent dissipating level that depends upon relative cost/price parameters. In high cost patches, the equilibrium density will be high, and it will be low in low cost patches. Once equilibrium biomass densities are determined for

¹³ It is important to point out that the status quo under consideration here is non-optimal and hence we are comparing various second-best alternatives. In this setting, we find that under certain circumstances a reserve can move the system closer to a first-best outcome. This is the only sense in which the double-dividend in this paper is related to the current double-dividend debate in the environmental economics literature.

each patch, these can be used to compute equilibrium effort and harvest levels. Note that the characteristics of each of the equilibria are determined by the type of biological dispersal system. At one end of the spectrum is what we might call a **closed** system, where there is no dispersal and the **D** matrix is null. In this case we simply have two independent patches, each equilibrating in a manner that is independent of the other patch. In contrast, when the system is **density dependent**, the equilibrium levels of effort are linked, and the level of effort in patch one is a function of economic parameters for both patches as well as the specific dispersal parameter. The **sink-source** case is a special case of the general density dependent dispersal mechanism (uni-directional) so that if patch one is the source patch, its equilibrium effort level will only be a function of its own parameters whereas in the sink patch, the equilibrium will depend upon parameters from both patches.

Table 1. Pre-reserve Bioeconomic Equilibria

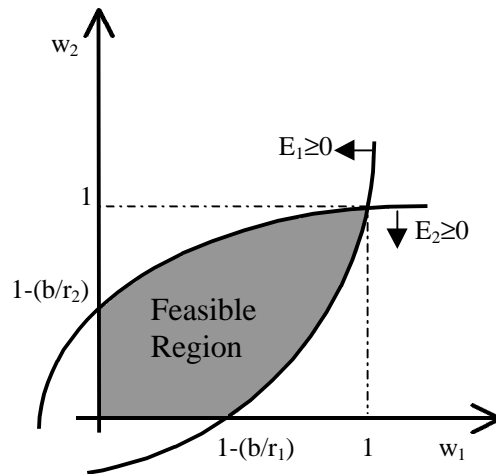
| Dispersal System | | Biomass Density | Effort Levels | Harvest Levels |
|--------------------------|------------|-----------------|---|---|
| Closed | Patch i | w_i | $E_i = \frac{r_i}{q_i}(1 - w_i)$ | $H_i = r_i w_i(1 - w_i)$ |
| Sink-Source | Source (i) | w_i | $E_i = \frac{r_i}{q_i}(1 - w_i) - \frac{b}{q_i}$ | $H_i = r_i w_i(1 - w_i) - b w_i$ |
| | Sink (j) | w_j | $E_i = \frac{r_i}{q_i}(1 - w_i) + \frac{b}{q_i}$ | $H_j = r_j w_j(1 - w_j) + b w_i$ |
| Density-Dependent | Patch i | w_i | $E_i = \frac{r_i}{q_i}(1 - w_i) + \frac{b}{q_i} \left(\frac{w_j}{w_i} - 1 \right)$ | $H_i = r_i w_i(1 - w_i) + b(w_j - w_i)$ |

Table 1 also indirectly reveals conditions necessary for interior pre-reserve equilibria. For example, in the closed case, positive effort levels require that the equilibrium biomass densities be profitable, which in turn requires that $w_i \equiv [(c_i + \pi)/p_i q_i]$ be less than one. This is intuitive, since it is equivalent to the condition that the marginal (and average) product of effort be positive at the equilibrium biomass density. The necessary conditions for interior solutions for the linked cases are more complicated and generally involve joint conditions associated with the parameters of both patches. For example, an interior solution in the density dependent case in which both patches attract positive pre-reserve effort calls for $r_i(1 - w_i) + b[(w_j/w_i) - 1] > 0$. Figure 1 graphs the implied parameter combinations that lead to an interior equilibrium in the density dependent case. Note that in a density dependent system, there are regions of cost/price ratios that would be sustainable in a closed system but that will not sustain an interior equilibrium in a linked system.¹⁴ In addition, the feasible interior solution region depends upon

¹⁴ For example, it can be seen that as b approaches zero (the closed system) all bioeconomic ratios in the interval $[0,1)$ allow interior solutions, which is not the case when $b > 0$.

cost/price ratios and other biological parameters in both patches; this reflects the fact that the harvest in any one patch is dependent upon the dispersal between the patches, which in turn depends upon relative densities and hence cost/price ratios in both patches. It is also the case that an interior open access equilibrium requires that the dispersal rate not be too high; in particular not higher than the intrinsic growth rate. This makes sense since if dispersal exceeds intrinsic growth, one would not expect to be able to sustain a biological equilibrium with positive biomass.¹⁵ In all of what follows, we will assume that the pre-reserve equilibrium is an interior equilibrium in which each patch is profitable to harvest before the reserve is established.

FIGURE 1
Existence Conditions
Two-Patch Density Dependent System



Now suppose that we wish to model the implications of creating a reserve in one of the patches, say patch one, by setting effort to zero in that patch and allowing entry/exit to proceed in the open patch until, in equilibrium, rents are zero. The impacts of reserve creation in the entire system depend most importantly upon two factors. First, the type of biological dispersal system (closed, sink-source, density dependent) is important, since biological linkages influence the manner in which biomass changes after reserve creation. Second, the biological and economic parameters are important, since they both determine the pre-reserve (status quo) equilibrium and influence the manner in which the system changes after reserve creation.

¹⁵ It can also be shown that as b approaches r (with $r_i=r$, for all i), the feasible region collapses to an open lens with intersections at zero and $[1,1]$. Thus as the dispersal rate increases, the feasible interior region gets smaller.

A. The Closed System

A few of the possibilities are obvious without much analysis. For example, suppose that we have a patchy but closed system, with no biological dispersal between patches. Suppose further that the pre-reserve equilibrium is an interior equilibrium in the sense that each patch is profitable to harvest. In this limiting case, creating a reserve eliminates harvest in the no-harvest patch, causing biomass to increase to its carrying capacity. Since the remaining patch is already at its bioeconomic equilibrium, and since there is no biological dispersal to disturb conditions in the open patch, there will be no change in the open part of the system as a result of the closure. Hence we have the following result:

Proposition 1: In a closed system with no biological linkages, creating a reserve by closing a patch will *increase* aggregate biomass and *decrease* aggregate harvest.

Reserves in this type of system thus contribute to the stock safety objective but at the expense of the industry. This could potentially set up circumstances for public conflict over reserve creation.

B. Sink-Source Systems

Consider another case with a biologically linked system. Suppose that we have a sink-source system with biomass flowing from patch one to patch two. Assume, as above, that the uni-directional flow is proportional to biomass density in patch one so that;

$$\begin{aligned}\dot{X}_1 &= r_1 X_1 (1 - X_1) - bX_1 - q_1 E_1 X_1 \\ \dot{X}_2 &= r_2 X_2 (1 - X_2) + bX_1 - q_2 E_2 X_2\end{aligned}\tag{7}$$

Before the reserve is put into place, biomass in patch one will be below carrying capacity and growth will be just matched by harvest and emigration. In patch two (the sink), biomass will equilibrate at a level where harvest just equals growth plus immigration. Now suppose that the **sink** is closed and designated a reserve. Then we can determine that:

Proposition 2: In a sink-source system with uni-directional density dependent flow, closing the sink will *increase* aggregate biomass and *decrease* aggregate harvest.

This can be seen as follows. The sink biomass will equilibrate where $\dot{X}_2 = 0 \Rightarrow r_2 X_2 (1 - X_2) + bX_1 = 0$, which will be at a higher biomass level than the pre-reserve level. At the same time, biomass in the source will be unchanged, since biomass flows uni-directionally **from** the source, and hence closing the sink will not affect dispersal or biomass in the source. In addition, since biomass is unaffected in the source and since it is already in a bioeconomic equilibrium there will be no impact on those harvesting the source. The net system effect will be a loss in harvest from the sink unmatched by any gain in the source, and a gain in biomass in the sink when harvesting is eliminated. Again there will be an increase in system biomass at the expense of the industry's

aggregate harvest, generating a potential conflict between those supporting reserves and the industry.

The other sink-source case, in which the **source** is designated a reserve, is more interesting because it sets up the possibility for both increases in aggregate biomass and harvest after the reserve is established. Whether a reserve will produce this "double dividend" or not depends upon system parameters, and as will be seen, certain configurations of both economic and biological circumstances will increase biomass and harvest after reserve creation. As above, we assume that $\dot{X}_1 = 0 \Rightarrow r_1 X_1(1 - X_1) - bX_1 - q_1 E_1 X_1 = 0$ and $\dot{X}_2 = 0 \Rightarrow r_2 X_2(1 - X_2) + bX_1 - q_2 E_2 X_2 = 0$ so that biomass flows in a unidirectional manner from patch one to two. In this case, closing the source will allow biomass to increase to a new unharvested equilibrium such that $\dot{X}_1 = 0 \Rightarrow r_1 X_1(1 - X_1) - bX_1 = 0$, or $X_1^R = 1 - (b/r_1)$. In the sink patch a bioeconomic equilibrium will be established such that $X_2^R = w_2 \equiv (c_2 + \pi)/p_2 q_2$. Hence the pre-reserve system biomass will be $w_1 k_1 + w_2 k_2$, whereas the post-reserve biomass will be $X_1^R k_1 + w_2 k_2$, with $X_1^R = 1 - (b/r_1)$. Therefore, system biomass increases when X_1^R is greater than w_1 . Note from Table 1, however, that the condition that ensures a pre-reserve interior equilibrium for the source patch requires that w_1 be less than $(1 - b/r_1)$. Hence the post reserve biomass density X_1^R will always be larger than the pre-reserve level w_1 and establishing a reserve in the source of a sink-source system increases overall biomass. These findings for the sink-source case are not surprising; closing a patch that was previously exploited will generally increase overall system biomass as the reserve seeks its new unexploited equilibrium. As discussed above, the more interesting issue is when does aggregate **harvest** also increase when a reserve is created? Recall that we found that when the **sink** is closed, aggregate harvest will fall. When the **source** is closed, in contrast, there is a chance that aggregate harvest can increase. This can be seen as follows. First note (from Table 1) that aggregate harvest without the reserve is simply $r_1 w_1(1 - w_1) + r_2 w_2(1 - w_2)$ or the sum of own growth in the pre-reserve equilibrium in each patch.¹⁶ After the source reserve is established, the source will equilibrate at $X_1^R = 1 - (b/r_1)$ and the sink will equilibrate where $\dot{X}_2 = 0 \Rightarrow r_2 w_2(1 - w_2) + bX_1^R - q_2 E_2 w_2 = 0$. But this suggests that the total harvest after the reserve is established is:

$$H_{reserve} = r_2 w_2(1 - w_2) + b[(1 - b/r_1)] \quad (8)$$

And we have:

Proposition 3: In a sink-source system with uni-directional flow, closing the source will *increase* aggregate biomass. Aggregate harvests will increase if:

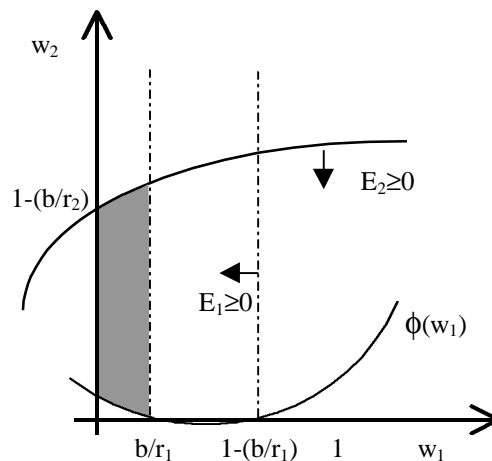
¹⁶ Note that this equation appears not to contain any contribution of dispersal to aggregate harvest. This is because while the equilibrium harvest in each patch equals the sum of own growth and dispersal, the extra harvest due to dispersal in the sink is precisely cancelled out by a corresponding subtraction of dispersal from the source.

$$\{b[1 - b/r_1] - bw_1\} - \{r_1 w_1(1 - w_1) - bw_1\} > 0 \tag{9}$$

Note that the first part of the inequality is the benefit from reserve creation, namely the increase in dispersal from the source due to a larger source biomass. The second term is the cost, namely the loss in pre-reserve harvest from the closed (source) area. The condition thus states the intuitively sensible result that system harvest will rise after closing the source patch if the gain in dispersal exceeds the harvest loss from the old pre-reserve source patch.

This condition can be met in a number of ways. Dropping the common bw_1 terms, the condition becomes one in economic and biological parameters $w_1 \equiv (c_1 + \pi/p_1 q_1)$ and b/r_1 . Figure 2 graphs some combinations of parameters where aggregate harvest increases when a source patch in a sink-source system is closed. The shaded area represents combinations of parameters that simultaneously satisfy the conditions for a pre-reserve interior equilibrium (E_1 and E_2 both greater than or equal to zero) and also (9) above. The condition allowing aggregate harvests to increase is plotted on Figure 2 as follows. First, consider condition (9) as an equality $(b/r_1)[1 - (b/r_1)] - w_1(1 - w_1) = 0$. This function is labeled $\phi(w_1)$ and is quadratic in w_1 with a value of zero at the two real values of w_1 symmetric around $(1/2)$, namely, $w_1 = b/r_1$ and $w_1 = 1 - (b/r_1)$.¹⁷ The function also is $(b/r_1)[1 - (b/r_1)]$ when w_1 is zero and it falls until $w_1 = 1/2$ and then rises. For circumstances that lead to aggregate harvest increasing after reserve formation, we need to look for values of w_1 which make the inequality in (9) positive, generally small and large values. But the large values can be eliminated from consideration because these will not satisfy the interior equilibrium requirements and hence we are left with the shaded area.

FIGURE 2
Double Dividend Conditions
Sink-Source Case



¹⁷ Figure 2 is drawn with b/r_1 less than $1/2$. If b/r_1 is greater than $1/2$, the function will look the same except that the two values where w_1 intersects zero will be transposed on the axis.

What does this tell us intuitively about the economic circumstances that lead to a double dividend? First, for any pre-reserve conditions in the sink, a double dividend will be more likely to arise if source patch cost/price ratios are very low. A bit of reflection suggests why. When source patch costs are low (or prices high), the pre-reserve biomass density will be driven to a low level through open access rent dissipation. Under these situations, there are two factors boosting the possibility of aggregate harvest gains. First, with a low biomass, the harvest in the source will also be low and hence the opportunity costs (in foregone harvests) from closure will be low. Second, with a low initial biomass, when the source is closed the corresponding increase in biomass in the closed patch will be large. Since the increase in dispersal into the open patch depends upon the patch density differential before and after the reserve, the gain in dispersal into the sink will also be large under these conditions.

What biological conditions favor an increase in harvest after reserve creation? Note that the above condition in (9) depends not only upon economic factors embedded in w_1 , but also biological factors embedded in the ratio b/r_1 . First, hold r_1 fixed, and vary the dispersal rate b . If the dispersal rate is very low, then the range of circumstances giving rise to the double dividend is constricted. This is the case because with low dispersal rates, closing the source doesn't yield a comparatively high payoff in the sink. Alternatively, if b is very high to begin with, then the equilibrium biomass density in the source patch after reserve formation will be low, and there won't be a large change in dispersal after reserve formation. One can see, in fact, that dispersal rates that are not too high or too low relative to r_1 are most likely to lead to conditions favoring an aggregate harvest increase after reserve formation.¹⁸ Similar reasoning applies to the intrinsic growth rate in the source patch; if r_1 is low, relative to the dispersal rate, the source patch equilibrium level will be low and it will be less likely for the reserve to generate increases in harvests.

C. Density Dependent Systems

Consider next the density dependent case in which:

$$\begin{aligned}\dot{X}_1 &= r_1 X_1 (1 - X_1) + b(X_2 - X_1) - q_1 E_1 X_1 \\ \dot{X}_2 &= r_2 X_2 (1 - X_2) + b(X_1 - X_2) - q_2 E_2 X_2\end{aligned}\tag{10}$$

In this system, before the reserve is established, entry will occur in each patch until net rents are driven to zero at some equilibrium population densities (w_1, w_2) determined by economic parameters. These equilibrium densities can then be used to solve for the corresponding equilibrium levels of effort and harvest as depicted in Table 1. We assume that the conditions are satisfied for a pre-reserve interior equilibrium as illustrated in Figure 1. Now assume that patch one is closed, creating a reserve. Under the assumptions made here, the biomass

¹⁸ In fact, when $b/r_1=1/2$ the range of w_1 satisfying (9) is largest.

density level in patch two will remain w_2 , but patch one density will grow until the first equation in (9) is satisfied (with zero harvest) at:

$$X_1^R = \frac{1}{2} \left(\frac{r_1 - b}{r_1} \right) + \frac{1}{2} \sqrt{\left(\frac{r_1 - b}{r_1} \right)^2 + 4 \frac{b}{r_1} w_2} \quad (11)$$

Since the sum of biomass in the system before the reserve is $w_1 k_1 + w_2 k_2$ and the sum after the reserve is established is $X_1^R k_1 + w_2 k_2$, there will be an increase in aggregate biomass after the reserve is formed in a density dependent system when (11) is greater than w_1 .

As it turns out, it is easy to show that if the pre-reserve equilibrium is an interior equilibrium, then X_1^R is greater than w_1 always.¹⁹ In other words, if there is some effort and harvesting taking place in a patch before that patch is designated a reserve, that patch will always equilibrate at a higher biomass density than its pre-reserve equilibrium. Thus reserve creation in a density dependent system will always increase aggregate system biomass.

What happens to aggregate harvests when a reserve is created in a density dependent system? Returning to Table 1, note that aggregate harvests before the reserve are $r_1 w_1 (1 - w_1) + r_2 w_2 (1 - w_2)$. After a reserve is created in patch 1, aggregate harvest will be $r_2 w_2 (1 - w_2) + r_1 X_1^R (1 - X_1^R)$. Hence aggregate harvests increase after reserve formation if:

$$H_{\text{reserve}} > H_{\text{no reserve}} \quad \text{if } r_1 X_1^R (1 - X_1^R) > r_1 w_1 (1 - w_1) \quad (12)$$

with X_1^R given in (11). But this expression can be rearranged to get:

$$(X_1^R - w_1) > [(X_1^R)^2 - (w_1)^2] = (X_1^R - w_1)(X_1^R + w_1) \quad (13)$$

Since $(X_1^R - w_1)$ is positive, we can divide through to get the condition:

$$X_1^R + w_1 < 1 \quad (14)$$

as defining the circumstances that lead to a double dividend in the density dependent case. After substituting equation (11) for X_1^R and rearranging, we get the condition, expressed in terms of economic and biological parameters, that:

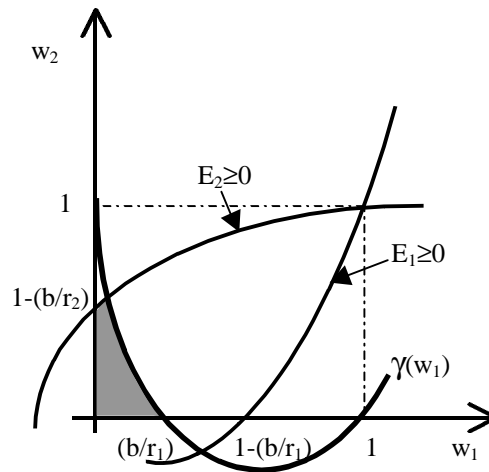
Proposition 4: In a density-dependent system, creating a reserve by closing a patch will *increase* aggregate biomass. Aggregate harvest will *increase* if:

$$\{(r_1/b)(w_1^2) - w_1 [1 + (r_1/b)] + 1\} > w_2 \quad (15)$$

¹⁹ This can be seen as follows. First begin with the inequality condition that guarantees E_1 to be positive. Then add $\{(1/2)[1 - (b/r_1)]\}^2$ to both sides and rearrange to get equation (8). Take the square root of both sides and rearrange again to show X_1^R greater than w_1 .

The function on the left of the inequality has a value of one when $w_1=0$, a value of zero when $w_1=1$, and it has zero points at $w_1=1$ and $w_1=(b/r_1)$, symmetrically located around the minimum at $w_1=(1/2)[1+(b/r_1)]$. Figure 3 plots the left-hand side of the inequality as a function of w_1 , labeled $\gamma(w_1)$. Figure 3 also plots all feasible points that satisfy the conditions for an interior equilibrium by showing regions of parameters for which E_1 and E_2 are positive. The intersection of these with the conditions generating a double dividend is shown in the shaded region.

FIGURE 3
Double Dividend Conditions
Density-Dependent Case



In a manner similar to the sink-source case, the density dependent case allows for the possibility that closing one patch may actually increase aggregate harvest in addition to increasing aggregate biomass. Again, whether this is possible or not depends upon whether the increased dispersal between the reserve and the open area compensates for the foregone harvest in the reserve. As was the case with the sink-source system, a double dividend is more likely to emerge when the patch to be closed is at a low level before the reserve is established. If this is the case, it is more likely that reserve formation will cost less (in foregone harvests) and benefit the industry more (in large reserve biomass levels and high dispersal to the open area). A difference between the density dependent case and the unidirectional sink-source case is that economic conditions in the open area also matter. For given economic parameters associated with the reserve patch, a double dividend is more likely when the open patch is not too dissimilar. For example, if the cost/price ratio is high in the reserve patch, a double dividend will be more likely if the cost/price ratio also is high in the open patch. This result occurs because the dispersal between the two patches is dependent upon relative densities. If cost/price ratios in the open patch are high, its pre-reserve density

will also be high. But this will lead to pre-reserve dispersal from the open patch to the patch designated as the reserve. When the reserve is actually created, biomass density in the reserve will have to increase substantially to reverse the dispersal flow and begin to create any positive benefits in the open patch.

The biological parameters interact in a more complicated way with density dependence compared with the sink-source system. In a similar manner, as the dispersal rate b falls, the parameter space likely to lead to double dividends also shrinks, and for similar reasons. As the dispersal rate gets large (relative to r_1), there are two offsetting effects. First, the potential double dividend region of combinations of (w_1, w_2) gets larger. But as b gets larger, the region in which a feasible interior pre-reserve equilibrium can be established shrinks. The combination of these effects determines the size of the region yielding a double dividend after reserve formation. Note also that other things equal, as r_1 rises, the feasible region for a possible double dividend shrinks. The intuition behind this conclusion is obvious; since the equilibrium level of the pre-reserve harvest in the patch to be closed is positively related to its own growth rate, the opportunity cost of closing a patch is higher when r_1 is large. Looked at an alternative way, the losses from closure will be large when r_1 is large and hence it is less likely that they can be overcome by increased dispersal. Correspondingly, as the growth rate in the open area r_2 gets larger, the region of w_2 over which double dividends are possible also rises. Higher levels of own growth in the receptor patch (relative to the dispersal rate) will support harvests under higher cost conditions than lower growth levels.

IV. DISCUSSION

The notion of setting aside areas of marine habitat as reserves has been gaining increasing support from several quarters over the past several years. Some proponents of marine reserves draw analogies with terrestrial reserves. As they point out, since we have examples of relatively undisturbed and unexploited terrestrial habitats, so too should we create similar set-asides in marine environments. The social benefits of these are only implied, but they seem to revolve around the desirability of having "natural" areas for study and for their inherent existence value. Another group of prominent proponents sees marine reserves and set aside areas as new policy instruments for management. One argument cited by this group is based on the fundamental uncertainty, variability, and unpredictability of exploited systems. This group argues that conventional management measures based on estimating surplus yields and calculating allowable catches and fishing mortality for single species are essentially bankrupt. They further argue that the only viable alternative is to protect entire areas containing ecological complexes for periods of time so that they can recover their resilience under unexploited conditions. Another group views no harvest zones as potential ecological hot spots of high productivity, the protection of which would actually benefit surrounding exploited areas via transport and risk hedging spillovers. And lastly, some see set aside areas as simply one of several alternative ways to manage fishing effort, under the belief that area closures may constrain total fishing mortality over a fishery system.

As discussed in the introduction, the most vocal objections to marine reserves have come from fishermen presently exploiting areas under consideration as set-asides. From their perspective, marine reserve proposals are akin to asking them to give up harvesting rights. In most marine settings, of course, fishermen do not have legal "rights" to harvest and hence part of this public/private conflict may have to be settled in the courts and legislative process. At the same time, it seems sensible from a political perspective to look for circumstances that might appear attractive to both group. We have termed these "double dividend" circumstances, in which it might be possible to both increase aggregate biomass and aggregate harvest in a spatially linked system by closing one or more areas to exploitation.

Our analytical investigation shows that indeed, it is possible to increase both aggregate biomass and harvests under some circumstances. This exercise is non-trivial because we are comparing various second-best equilibria and whether it is possible to "improve" the status quo depends upon the nature of that initial position as well as the incentives that influence the change. We demonstrate that the double dividend issue is both a biological and economic problem. This bears emphasis because much of the literature on reserves either treats the problem as if it is a purely biological problem (e.g. close patches that are most productive) or with naive assumptions about harvesters' behavior (e.g. effort in closed areas simply disappears). As our analysis shows, closing an area in an exploited system always increases aggregate system biomass. Closing an area also increases aggregate harvests whenever the system dispersal benefits to the remaining open areas are large relative to foregone harvest. This means that dispersal mechanisms matter; closed systems will not generate any harvest benefits although they will increase aggregate biomass. With biologically linked systems, the types and relative strength of biological linkages are important. In a sink-source system, for example, since dispersal is dependent upon the source it is important to close the source rather than the sink, and whether harvesting gains are possible depends upon initial conditions in the source. If the source is relatively unprofitable, there will be little advantage to closing it because the pre-reserve biomass will already be relatively high. Similarly (and perhaps paradoxically) if the dispersal rate for a source is too high, it may not pay to close the patch. This is because with a high dispersal rate, there will already be a high "leakage" out of the source and creating a marine reserve will have relatively small impacts on the remaining open system. If the dispersal rate is too low, it also may not pay to create a reserve. With low dispersal, less is gained by closing an area; in the limiting case of the closed system one essentially gives up all the reserve harvest for no gain.

In the more general density dependent case, aggregate harvests again increase under certain specific conditions. When cost/price ratios in the reserve-designate are low, the initial position will be one characterized by overharvesting, a low biomass, and low sustained harvests. In this case, closing the area is achieved at little cost in foregone harvests and it generates the largest benefits since dispersal to the remaining open areas is proportional to the new higher biomass density. In extreme cases, closure may even cause dispersal to reverse direction. This points to another feature of general density dependent systems and that is that whether a patch is a de facto sink or source depends upon both biological and economic

factors. A low cost area may be driven to low biomass levels and hence become a sink in a general density dependent system *vis-a-vis* other lower cost patches. But closing low cost areas may reverse the biomass density gradient, causing the closed area to become a source for the remaining system. We also showed that a high intrinsic growth rate can work against the double dividend because high own growth rates increase the opportunity cost of closing an area. These types of conclusions seem to run counter to simple biological analyses which have treated the reserve selection issue as if it were one of simply finding and closing inherently high productivity areas.

REFERENCES

- Allison, Gary W., Jane Lubchenco, and Mark H. Carr. 1998. "Marine Reserves are Necessary but not Sufficient for Marine Conservation," *Ecological Applications*, vol. 8, no. 1, pp. s79-s92.
- Bhat, M. G., R. G. Huffaker, and S. M. Lenhart. 1993. "Controlling Forest Damage by Dispersive Beaver Populations: Centralized Optimal Management Strategy," *Ecological Applications*, vol. 3, no. 3, pp. 518-530.
- Bhat, M. G., R. G. Huffaker, and S. M. Lenhart. 1996. "Controlling Transboundary Wildlife Damage: Modeling Under Alternative Management Scenarios," *Ecological Modeling*, 92, pp. 215-224.
- Bohnsack, James A. 1993. "Marine Reserves: They Enhance Fisheries, Reduce Conflicts, and Protect Resources," *Oceanus*, Fall, pp. 63-71.
- Botsford, L. W., J. F. Quinn, Stephen R. Wing, and John G. Brittnacher. 1993. *Rotating Spatial Harvest of a Benthic Invertebrate, the Red Sea Urchin, Strongylocentrotus franciscanus*, International symposium on Management Strategies for Exploited Fish Populations: Alaska Sea Grant College Program.
- Brown, G. M., and J. Roughgarden. 1997. "A metapopulation model with private property and a common pool," *Ecological Economics*, vol. 22, no. 1, pp. 65-71.
- Carr, M. H., and Daniel C. Reed. 1993. "Conceptual Issues Relevant to Marine Harvest Refuges: Examples from Temperate Reef Fishes," *Canadian Journal of Fisheries and Aquatic Sciences*, 50, pp. 2019-2028.
- Davis, Gary E. 1989. "Designated Harvest Refugia: The Next Stage of Marine Fishery Management in California," *CalCoFl Rep*, 30, pp. 53-58.
- Dugan, Jenifer E., and Gary E. Davis. 1993. "Applications of Marine Refugia to Coastal Fisheries Management," *Canadian Journal of Fisheries and Aquatic Sciences*, 50, pp. 2029-2042.
- Gordon, H. S. 1954. "The Economic Theory of a Common-Property Resource: The Fishery," *Journal of Political Economy*, 62, pp. 124-142.
- Hannesson, Rognvaldur. 1998. "Marine Reserves: What will they accomplish?" mimeo, Centre for Fisheries Economics, The Norwegian School of Economics and Business Administration.
- Hastings, A. 1982. "Dynamics of a single species in a spatially varying habitat: The stabilizing role of high dispersal rates," *Journal of Mathematical Biology*, 16, pp. 49-55.
- Hastings, A. 1983. "Can spatial variation alone lead to selection for dispersal," *Theoretical Population Biology*, 24, pp. 244-251.

- Hastings, A., and Susan Harrison. 1994. "Metapopulation dynamics and genetics," *Annual Review of Ecology and Systems*, 25, pp. 167-188.
- Holland, Daniel S., and Richard J. Brazee. 1996. "Marine Reserves for Fisheries Management," *Marine Resource Economics*, 11, pp. 157-171.
- Holt, R. D. 1985. "Population Dynamics in two-patch environments: Some anomalous consequences of an optimal habitat distribution," *Theoretical Population Biology*, 28, pp. 181-208.
- Huffaker, R. G., M. G. Bhat, and S. M. Lenhart. 1992. "Optimal trapping strategies for diffusing nuisance-beaver populations," *Natural Resource Modeling*, vol. 6, no. 1, pp. 71-97.
- Lauck, Tim, Colin W. Clark, Marc Mangel, and Gordon R. Munro. 1998. "Implementing the precautionary principle in fisheries management through marine reserves," *Ecological Applications*, vol. 8, no. 1, pp. s72-s78.
- Levin, S. A. 1974. "Dispersion and Population Interactions," *American Naturalist*, 108, pp. 207-227.
- Levin, S. A. 1976. "Population dynamic models in heterogeneous environments," *Annual Review of Ecology and Systems*, 7, pp. 287-310.
- Man, Alias, Richard Law, and Nicholas V. C. Polunin. 1995. "Role of Marine Reserves in Recruitment to Reef Fisheries: A Metapopulation Model," *Biological Conservation*, 71, pp. 197-204.
- Polacheck, Tom. 1990. "Year Around Closed Areas as Management Tool," *Natural Resource Modeling*, vol. 4, no. 3, pp. 327-354.
- Possingham, H. P., and J. Roughgarden. 1986. "Spatial population dynamics of a marine organism with a complex life cycle," *Ecology*, vol. 71, no. 3, pp. 973-985.
- Pulliam, H. R. 1988. "Sources, Sinks, and population regulation," *American Naturalist*, 132, pp. 652-661.
- Quinn, J. F., Stephen R. Wing, and L. W. Botsford. 1993. "Harvest Refugia in Marine Invertebrate Fisheries: Models and Applications to the Red Sea Urchin, *Strongylocentrotus franciscanus*," *American Zoologist*, 33, pp. 537-550.
- Roberts, Callum M., and Nicholas V. C. Polunin. 1991. "Are Marine Reserves Effective in Management of Reef Fisheries?" *Reviews in Fish Biology and Fisheries*, 1, pp. 65-91.
- Roughgarden, J. 1974. "Population Dynamics in a Spatially Varying Environment: How Population Size 'Tracks' Spatial Variation in Carrying Capacity," *American Naturalist*, 108, pp. 649-664.
- Roughgarden, J., and Y. Iwasa. 1986. "Dynamics of a metapopulation with space-limited subpopulations," *Theoretical Population Biology*, 29, pp. 235-261.

- Sanchirico, James N., and James E. Wilen. 1996. *The Bioeconomics of Marine Reserves*, selected paper presented at the European Environmental and Resource Economics Conference, Lisbon, Portugal.
- Sanchirico, James N., and James E. Wilen. 1999. "Bioeconomics of Spatial Exploitation in a Patchy Environment," *Journal of Environmental Economics and Management*, forthcoming, March 1999.
- Schulz, C. E., and A. Skonhofs. 1996. "Wildlife Management, Land-Use and Conflicts," *Environment and Development Economics*, 1, pp. 265-280.
- Skonhofs, A., and J. T. Solstad. 1996. "Wildlife Management, Illegal Hunting and Conflicts. A Bioeconomic Analysis," *Environment and Development Economics*, 1, pp. 165-181.
- Smith, V. L. 1968. "Economics of Production from Natural Resources," *American Economic Review*, pp. 409-431.
- Smith, V. L. 1969. "On Models of Commercial Fishing," *Journal of Political Economy*, 77, pp. 181-198.
- Tuck, Geoffrey N., and Hugh P. Possingham. 1994. "Optimal Harvesting Strategies for a Metapopulation," *Bulletin of Mathematical Biology*, vol. 56, no. 1, pp. 107-127.
- Vance, R. 1984. "The effects of dispersal on population stability in one-species, discrete space population growth models," *American Naturalist*, vol. 123, no. 2, pp. 230-254.