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# The Bioeconomics of Marine Sanctuaries

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# The Bioeconomics of Marine Sanctuaries

*Abstract*

The role of a marine sanctuary, where commercial fishing might be prohibited, is evaluated in two models; one where net biological growth is deterministic, and the other where net biological growth is stochastic. There is diffusion (migration) between the sanctuary and the fishing grounds based on the ratios of current stock size to carrying capacity in each area. Fishing is managed under a regime of regulated open access. In the deterministic model, it is possible to determine the steady-state equilibrium and to assess its local stability. In the stochastic model a steady state does not exist, but a stable joint distribution for the fish stock on the grounds and in the sanctuary is possible. The creation of a no-fishing marine sanctuary leads to higher population levels on the grounds and in the sanctuary, and appears to reduce the variation of the population in both areas. The higher population levels and reduced variation has an opportunity cost; foregone harvest from the sanctuary.

**Keywords:** population dynamics, fishing, marine sanctuaries, regulated open access, diffusion.

# The Bioeconomics of Marine Sanctuaries

## I. Introduction and Overview

Marine sanctuaries have been established in many countries as a means of protecting endangered species or entire ecosystems. In the US, Title III of the Marine Protection, Research and Sanctuaries Act of 1972 established the National Marine Sanctuaries Program (NMSP). The goal of the program is to establish a system of sanctuaries that (1) provide enhanced resource protection through conservation and management, (2) facilitate scientific research, (3) enhance public awareness, understanding, and appreciation of the marine environment, and (4) promote the appropriate use of marine resources.

There are currently twelve sanctuaries in the US system. Eleven of these appear to have been established for the primary purpose of resource conservation. The twelfth site protects the wreck of the *USS Monitor*, a Civil War vessel of historical significance. The sanctuaries, their size, and some of their key species are summarized in Table 1.

The National Oceanic and Atmospheric Administration (NOAA) is charged with the management of the system, and has the power to impose additional regulations on fishing or other activities within a sanctuary. Some additional regulations have been placed on fishing within six of the marine sanctuaries, primarily to protect coral reefs and benthic habitat. A sanctuary system, however, has the potential to serve as a haven for species sought by commercial or sport fishers, and thus as a source, or inventory, of species that could replenish or recolonize areas that have been more intensively harvested.

The purpose of this paper is to examine the role that a marine sanctuary might play when it is adjacent to an area supporting a commercial fishery (called the "grounds"). A sanctuary may come under the same regulatory policies as imposed on the grounds, or it may be subject to additional regulations, up to and including a prohibition on fishing. In this paper it will be assumed that the grounds are managed as a regulated, open-access fishery, as described by Homans and Wilen (1997). The dynamics of the commercially harvested species is influenced by a diffusion process between the grounds and the sanctuary similar to that of the inshore/offshore fishery described in Clark (1990). The role of the sanctuary will be examined when net growth is deterministic and when it is stochastic.

The rest of the paper is organized as follows. In the next section a general, deterministic model of sanctuary and grounds is constructed. Conditions for stability of the regulated, open-access equilibrium are presented. In Section III the deterministic model is modified to allow for stochastic net biological growth. The stochastic model will not possess a steady state, but may lead to a stable joint distribution for the commercial species on the grounds and in the sanctuary. This distribution will shift in phase space if the sanctuary is placed under more restrictive regulation, such as prohibition of fishing.

In Section IV a numerical example is developed. The stability of equilibria in the deterministic model is easily analyzed. This analysis can indicate the neighborhood in phase space where a stable stochastic system will fluctuate. The fifth section recaps the major conclusions on the role of marine sanctuaries in both deterministic and stochastic environments.

## II. The Deterministic Model

Consider the situation where a single species is commercially harvested in two adjacent areas. Area One has recently been designated as a marine sanctuary. Both areas are currently managed under a regime of regulated open access, although fishing in the sanctuary could be further restricted.

In period t, let $X_{1,t}$ denote the biomass of the commercial species in the sanctuary and $X_{2,t}$ the biomass of the same species on the grounds. With harvest in both areas, and diffusion between, we have a dynamical system that might be characterized by the difference equations

$$\begin{aligned} X_{1,t+1} &= X_{1,t} + F_1(X_{1,t}) - D(X_{1,t}, X_{2,t}) - \phi_1(X_{1,t}) \\ X_{2,t+1} &= X_{2,t} + F_2(X_{2,t}) + D(X_{1,t}, X_{2,t}) - \phi_2(X_{2,t}) \end{aligned} \tag{1}$$

where $F_1(\bullet)$ and $F_2(\bullet)$ are net growth functions, $D(\bullet)$ is a diffusion function, and $Y_{1,t} = \phi_1(X_{1,t})$ and $Y_{2,t} = \phi_2(X_{2,t})$ are the policy functions used by the management authorities to determine total allowable catch (TAC) in Areas One and Two, respectively. The sequence of growth, diffusion and harvest is as follows. At the beginning of each period, net growth takes place based on the biomass levels in each area. This is followed by migration or diffusion, which will depend on biomass and carrying capacity in both areas. The diffusion function has been arbitrarily defined as the net migration from the sanctuary to the grounds. If $D(X_{1,t},X_{2,t}) > 0$, fish, on net, are leaving the sanctuary. If $D(X_{1,t},X_{2,t}) < 0$ fish, on net, are leaving the grounds. Lastly, harvest takes place, reducing biomass in both areas.

In the model of regulated open access it is assumed that the TACs, as determined by the policy functions $Y_{1,t} = \phi_1(X_{1,t})$ and $Y_{2,t} = \phi_2(X_{2,t})$, are binding. This implies that the actual level of harvest in each area will equal the TAC, which will also equal the level of harvest as defined by the fishery production function for each area. The fishery production function relates stock, effort and season duration to harvest in each period. The production functions are denoted as $Y_{1,t} = H_1(X_{1,t}, E_{1,t}, T_{1,t})$ and $Y_{2,t} = H_2(X_{2,t}, E_{2,t}, T_{2,t})$ where $E_{i,t}$ is the level of fishing effort committed to the ith area at the beginning of period t and $T_{i,t}$ is the duration or season length in the ith area, i=1,2. When actual harvest in an area reaches its TAC, fishing stops, and the area is closed for the rest period. By equating $\phi_i(X_{i,t})$ with $H_i(X_{i,t},E_{i,t},T_{i,t})$ we have a single equation in three unknowns and we can solve for season length as a function of stock and effort. This implicit relationship is written as $T_{i,t} = \varphi_i(X_{i,t},E_{i,t})$.

Under regulated open access, fishers are thought to commit to a level of effort that "dissipates rent," driving net revenue to zero. Net revenue in the ith area in period t is given by the expression

$$\pi_{i,t} = pH_i(X_{i,t}, E_{i,t}, \varphi_i(X_{i,t}, E_{i,t})) - v_i E_{i,t} \varphi_i(X_{i,t}, E_{i,t}) - f_i E_{i,t} \qquad (2)$$

The first term on the right-hand-side (RHS) is revenue in period t from harvesting the TAC in area i, where p is the unit price for fish on the dock. Note, that the expression $\varphi_i(\bullet)$ has been substituted into the production functions for $T_{i,t}$. The second term is variable cost, $v_i E_{i,t} T_{i,t}$, where $v_i > 0$ and $\varphi_i(\bullet)$ has again been substituted for $T_{i,t}$. The third term is the fixed cost of the $E_{i,t}$ units of effort fishing in the ith area, where $f_i > 0$. Net revenue in the ith area is a function of only $X_{i,t}$ and $E_{i,t}$. Setting $\pi_{i,t} = 0$, we can solve for $E_{i,t} = \psi_i(X_{i,t})$.

The dynamics of the species in each area, the TACs, effort and season length can be simulated from $(X_{1,0},X_{2,0})$ by the augmented system

$$
\begin{aligned}
X_{1,t+1} &= X_{1,t} + F_1(X_{1,t}) - D(X_{1,t}, X_{2,t}) - \phi_1(X_{1,t}) \\
X_{2,t+1} &= X_{2,t} + F_2(X_{2,t}) + D(X_{1,t}, X_{2,t}) - \phi_2(X_{2,t}) \\
Y_{1,t} &= \phi_1(X_{1,t}) \\
Y_{2,t} &= \phi_2(X_{2,t}) \\
E_{1,t} &= \psi_1(X_{1,t}) \\
E_{2,t} &= \psi_2(X_{2,t}) \\
T_{1,t} &= \varphi_1(X_{1,t}, \psi_1(X_{1,t})) \\
T_{2,t} &= \varphi_2(X_{2,t}, \psi_2(X_{2,t}))
\end{aligned} \tag{3}
$$

where the RHSs of all the expressions in (3) depend only on $X_{1,t}$ and $X_{2,t}$.

Up to now we have made no assumptions about the functions $F_i(\bullet)$, $D(\bullet)$, and $\phi_i(\bullet)$. If these functions are nonlinear, system (3) is capable of a rich set of dynamic behaviors, including convergence to one or more steady states, periodic cycles, and possibly deterministic chaos. System (3) is driven by the first two difference equations and the local stability of a steady state can be determined as follows. First, the steady state equilibria of the system can be found by searching for the pairs $(X_1,X_2)$ which satisfy

$$
\begin{aligned}
G_1(X_1, X_2) &= F_1(X_1) - D(X_1, X_2) - \phi_1(X_1) = 0 \\
G_2(X_1, X_2) &= F_2(X_2) + D(X_1, X_2) - \phi_2(X_2) = 0
\end{aligned} \tag{4}
$$

For a particular steady state to be locally stable the characteristic roots of the matrix A must be less than one in absolute value or have real parts that are less than one in absolute value. The matrix A is defined by

$$
A = \begin{bmatrix} a_{1,1}(X_1, X_2) & a_{1,2}(X_1, X_2) \\ a_{2,1}(X_1, X_2) & a_{2,2}(X_1, X_2) \end{bmatrix} \tag{5}
$$

where

$$
\begin{aligned}
a_{1,1}(X_1, X_2) &= 1 + F_1'(X_1) - \partial D(X_1, X_2)/\partial X_1 - \phi_1'(X_1) \\
a_{1,2}(X_1, X_2) &= -\partial D(X_1, X_2)/\partial X_2 \\
a_{2,1}(X_1, X_2) &= \partial D(X_1, X_2)/\partial X_1 \\
a_{2,2}(X_1, X_2) &= 1 + F_2'(X_2) + \partial D(X_1, X_2)/\partial X_2 - \phi_2'(X_2)
\end{aligned}
\tag{6}
$$

Defining $\beta = a_{1,1}(\bullet) + a_{2,2}(\bullet)$ and $\gamma = a_{1,1}(\bullet)a_{2,2}(\bullet) - a_{1,2}(\bullet)a_{2,1}(\bullet)$, the characteristic roots of A will be given by

$$
\lambda_i = \frac{\beta \pm \sqrt{\beta^2 - 4\gamma}}{2}, \quad i = 1, 2 \tag{7}
$$

## III. The Stochastic Model

It is frequently the case that fish and shellfish populations exhibit significant fluctuations in recruitment as the result of stochastic processes in the marine environment. Marine sanctuaries might serve as a buffer against such processes. One way of modeling this stochasticity would be to premultiply the net growth functions by a random variable such as $z_{i,t+1}$, in the system below.

$$
\begin{aligned}
X_{1,t+1} &= X_{1,t} + z_{1,t+1}F_1(X_{1,t}) - D(X_{1,t}, X_{2,t}) - \phi_1(X_{1,t}) \\
X_{2,t+1} &= X_{2,t} + z_{2,t+1}F_2(X_{2,t}) + D(X_{1,t}, X_{2,t}) - \phi_2(X_{2,t})
\end{aligned}
\tag{8}
$$

Depending on the size and proximity of our two areas, $z_{1,t+1}$ and $z_{2,t+1}$ may be highly correlated. System (8), and the augmented system of regulated open access, will not have a steady state, but may exhibit a stable joint distribution in $(X_{1,t}, X_{2,t})$ space. It is not likely that an analytic form for the joint distribution can be deduced from a knowledge of the distributions for $z_{i,t+1}$, but simulation of the stochastic system will permit the calculation of descriptive statistics for the joint distribution, both with and without additional restrictions on fishing in the sanctuary.

## IV. A Numerical Example

To illustrate the procedures for determining steady state and stability in the deterministic model and the joint distribution of $(X_{1,t}, X_{2,t})$ in the stochastic model, we turn to a numerical example. We adopt the following functional forms: $F_1(\bullet) = r_1X_{1,t}(1 - X_{1,t}/K_1)$, $F_2(\bullet) = r_2X_{2,t}(1 - X_{2,t}/K_2)$, $D(\bullet) = s(X_{1,t}/K_1 - X_{2,t}/K_2)$, $\phi_1(\bullet) = c_1 + d_1X_{1,t}$, $\phi_2(\bullet) = c_2 + d_2X_{2,t}$, $H_1(\bullet) = X_{1,t}(1 - e^{-q_1E_{1,t}T_{1,t}})$, and $H_2(\bullet) = X_{2,t}(1 - e^{-q_2E_{2,t}T_{2,t}})$.

The forms for $F_1(\bullet)$ and $F_2(\bullet)$ are logistic, where $r_1$ and $r_2$ are positive intrinsic growth rates, and $K_1$ and $K_2$ are positive carrying capacities. The diffusion function, with $s > 0$, presumes that there will be out-migration from the sanctuary if $X_{1,t}/K_1 > X_{2,t}/K_2$, and in-migration if $X_{1,t}/K_1 < X_{2,t}/K_2$. This implies out-migration from the area with the higher ratio of stock to carrying capacity.

The TAC policy rules, $\phi_i(\bullet)$, presume a linear relationship between the TAC and $X_{i,t}$. The slope coefficient is presumably positive ($d_i > 0$), while the intercept ($c_i$) might be positive, zero or negative. The form of the production functions, $H_i(\bullet)$, presumes that net growth is followed a process of continuous fishing for a season of length $T_{i,t}$, and that the stock, $X_{i,t}$, is subject to pure depletion during the season.

Equating $\phi_i(\bullet)$ with $H_i(\bullet)$ and solving for $T_{i,t}$ yields

$$T_{i,t} = \varphi_i(X_{i,t}, E_{i,t}) = \left(\frac{1}{q_iE_{i,t}}\right)\ln\left[\frac{X_{i,t}}{(1-d_i)X_{i,t} - c_i}\right] \quad (9)$$

The expression for net revenue is given by

$$\pi_{i,t} = pX_{i,t}(1 - e^{-q_i E_{i,t} T_{i,t}}) - v_i E_{i,t} T_{i,t} - f_i E_{i,t} \tag{10}$$

Substituting the (9) into (10), setting $\pi_{i,t} = 0$, and solving for $E_{i,t}$ yields

$$E_{i,t} = (p/f_i)(c_i + d_i X_{i,t}) - [v_i/(q_i f_i)] \ln\left[\frac{X_{i,t}}{(1-d_i)X_{i,t} - c_i}\right] \tag{11}$$

The augmented system takes the form

$$\begin{aligned}
X_{1,t+1} &= X_{1,t} + r_1 X_{1,t}(1 - X_{1,t}/K_1) - s(X_{1,t}/K_1 - X_{2,t}/K_2) - (c_1 + d_1 X_{1,t}) \\
X_{2,t+1} &= X_{2,t} + r_2 X_{2,t}(1 - X_{2,t}/K_2) + s(X_{1,t}/K_1 - X_{2,t}/K_2) - (c_2 + d_2 X_{2,t}) \\
Y_{1,t} &= c_1 + d_1 X_{1,t} \\
Y_{2,t} &= c_2 + d_2 X_{2,t} \\
E_{1,t} &= (p/f_1)(c_1 + d_1 X_{1,t}) - [v_1/(q_1 f_1)] \ln\left[\frac{X_{1,t}}{(1-d_1)X_{1,t} - c_1}\right] \\
E_{2,t} &= (p/f_2)(c_2 + d_2 X_{2,t}) - [v_2/(q_2 f_2)] \ln\left[\frac{X_{2,t}}{(1-d_2)X_{2,t} - c_2}\right] \\
T_{1,t} &= \left(\frac{1}{q_1 E_{1,t}}\right) \ln\left[\frac{X_{1,t}}{(1-d_1)X_{1,t} - c_1}\right] \\
T_{2,t} &= \left(\frac{1}{q_2 E_{2,t}}\right) \ln\left[\frac{X_{2,t}}{(1-d_2)X_{2,t} - c_2}\right]
\end{aligned} \tag{12}$$

If a steady state to system (12) exists it must satisfy

$$\begin{aligned}
G_1(X_1, X_2) &= r_1 X_1(1 - X_1/K_1) - s(X_1/K_1 - X_2/K_2) - (c_1 + d_1 X_1) = 0 \\
G_2(X_1, X_2) &= r_2 X_2(1 - X_2/K_2) + s(X_1/K_1 - X_2/K_2) - (c_2 + d_2 X_2) = 0
\end{aligned} \tag{13}$$

The elements of the matrix A are

$$
\begin{aligned}
a_{1,1} &= 1 + r_1(1 - 2X_1/K_1) - s/K_1 - d_1 \\
a_{1,2} &= s/K_2 \\
a_{2,1} &= s/K_1 \\
a_{2,2} &= 1 + r_2(1 - 2X_2/K_2) - s/K_2 - d_2
\end{aligned}
\qquad (14)
$$

With values for $r_1$, $r_2$, $K_1$, $K_2$, $c_1$, $c_2$, $d_1$, $d_2$, and s, it would be possible to numerically solve for the pairs $(X_1,X_2)$ which satisfy (13) and to check for local stability based on the elements in (14). With $X_1$ and $X_2$, and values for $v_1$, $v_2$, $f_1$, $f_2$, $q_1$, $q_2$, and p, one could then solve for the steady-state values for $Y_1$, $Y_2$, $E_1$, $E_2$, $T_1$, and $T_2$. System (12) could be iterated forward in time from an initial condition $(X_{1,0},X_{2,0})$ to see if it converges to the previously calculated steady state.

This was done using parameter estimates for Areas 2 and 3 in the North Pacific halibut fishery [Homans and Wilen (1997, Table II)]. Area 2 was designated as the sanctuary and Area 3 as the grounds. The diffusion coefficient was set at $s = 100$. Steady values of $X_1$ and $X_2$, were obtained by driving $|G_1(\bullet)| + |G_2(\bullet)|$ to zero from a guess of $X_1 = 250$ and $X_2 = 200$ using Excel's Solver. Steady-state equilibria were determined when fishing was allowed in the sanctuary according to $Y_{1,t} = c_1 + d_1X_{1,t}$ and when fishing was prohibited ($c_1 = d_1 = 0$). The resulting equilibria and stability analysis are summarized in Table 2.

When fishing was allowed in the sanctuary $X_1 = 189.81$ million pounds out of a carrying capacity of $K_1 = 318$ million pounds and $X_2 = 249.79$ compared to a carrying capacity of $K_2 = 416$ million pounds. These stock levels implied a fleet of 47.55 vessels fishing for 3.09 days to obtain a harvest of 29.35 million pounds in the sanctuary and 23.54 vessels fishing 5.72 days to harvest 30.78 million pounds of halibut from the grounds. There is a small net migration of fish from the grounds to the sanctuary with $D(X_1,X_2) = -0.35$ million pounds.

When fishing is prohibited in the sanctuary, $X_1 = 282.74$ million pounds and $X_2 = 320.45$ million pounds. On the grounds, there are 27.95 vessels fishing 4.22 days to harvest 34.84 million pounds of halibut. With fishing prohibited in the sanctuary, there is a net migration of 11.88 million pounds from the sanctuary to the grounds.

In the stochastic model, the dynamics of the fish stock in the sanctuary and on the grounds are given by

$$X_{1,t+1} = X_{1,t} + z_{1,t+1}r_1X_{1,t}(1 - X_{1,t}/K_1) - s(X_{1,t}/K_1 - X_{2,t}/K_2) - (c_1 + d_1X_{1,t})$$
$$X_{2,t+1} = X_{2,t} + z_{2,t+1}r_2X_{2,t}(1 - X_{2,t}/K_2) + s(X_{1,t}/K_1 - X_{2,t}/K_2) - (c_2 + d_2X_{2,t}) \qquad (15)$$

where $z_{1,t+1}$ and $z_{2,t+1}$ are each independent and identically distributed random variables. It does not appear possible to derive the induced joint distribution for $X_{1,t}$ and $X_{2,t}$ based on a knowledge of the distributions for $z_{1,t+1}$ and $z_{2,t+1}$. The effect of a sanctuary in this stochastic environment was examined through simulation under the assumption that $z_{1,t+1}$ and $z_{2,t+1}$ were each independently distributed as uniform between zero and two [$z_{i,t+1}$~U(0,2), i=1,2]. Twenty realizations, with horizons t=0,1,...,50, were generated. Biomass levels were calculated with and without Area One as a sanctuary. When Area One was designated as a sanctuary, fishing was prohibited by setting $c_1 = d_1 = 0$. A typical realization is shown in Figure 1.

Assuming a transition from $X_{1,0} = 318$ and $X_{2,0} = 416$ over the subinterval t=0,1,...,9, mean biomass levels and their standard deviations were calculated for t=10,11,...,50 for each realization, both with and without sanctuary status for Area One. Grand means and average standard deviations were calculated over the twenty realizations. With no sanctuary, the average biomass in Area One was 191.42, while the average biomass in Area 2 was 251.47. Recall from Table 2, that if fishing was allowed in both areas in the deterministic model, a stable steady state existed at $X_1$ = 189.81 and $X_2$ = 249.79; figures that are very close to the average biomass after allowing for a transition from $(X_{1,0}, X_{2,0})$. The average standard deviation with fishing was $s_1$ = 20.49 and $s_2$ = 24.07 for Areas One and Two, respectively.

When Area One is designated as a sanctuary, and fishing is prohibited, the mean biomass after t=9 was $X_1$ = 283.01 in Area One, and $X_2$ = 320.63 in Area Two. These averages can be compared with the deterministic steady state from Table 2 where $X_1$ = 282.74 and $X_2$ = 320.45. With Area One a sanctuary, $s_1$ = 9.07 while $s_2$ = 15.81. Thus, the designation of Area One as a no-fishing sanctuary increased average biomass in both areas and reduced the variation about mean biomass levels that were essentially equal to those calculated for the steady state in the deterministic model.

## V. Conclusions

This paper has developed a model of regulated open access with diffusion between two areas in order to explore the potential role of a marine sanctuary. The role of a no-fishing sanctuary was analyzed in both a deterministic and stochastic marine environment. The deterministic model permitted the identification of regulated open access equilibria (steady states) with and without a sanctuary. The stability of any equilibrium in the deterministic model was easily assessed. In a numerical analysis of the North Pacific halibut fishery, designation of a no fishing sanctuary resulted in a stable equilibrium with higher equilibrium biomass levels in both areas. The sanctuary served as a significant source of fishable biomass that migrated to the grounds.

In the stochastic model, where intrinsic growth rates fluctuated between zero and twice their value as specified in the deterministic model, designation of a no-fishing sanctuary resulted in higher biomass and a lower standard deviations in both areas. While the higher biomass and lower variation with a sanctuary might be attractive to fishery managers, it comes at an opportunity cost of reduced yield from the combined areas. In the deterministic model, when fishing was allowed in both areas, a combined yield of $Y_1 + Y_2 = 60.14$ million pounds was achieved in steady state for the halibut fishery. When Area One was designated as a no-fishing sanctuary, the yield from Area Two was 34.84 million pounds, or 25.3 million pounds less than when fishing was allowed in both areas.

## Table 1. Marine Sanctuaries in the United States

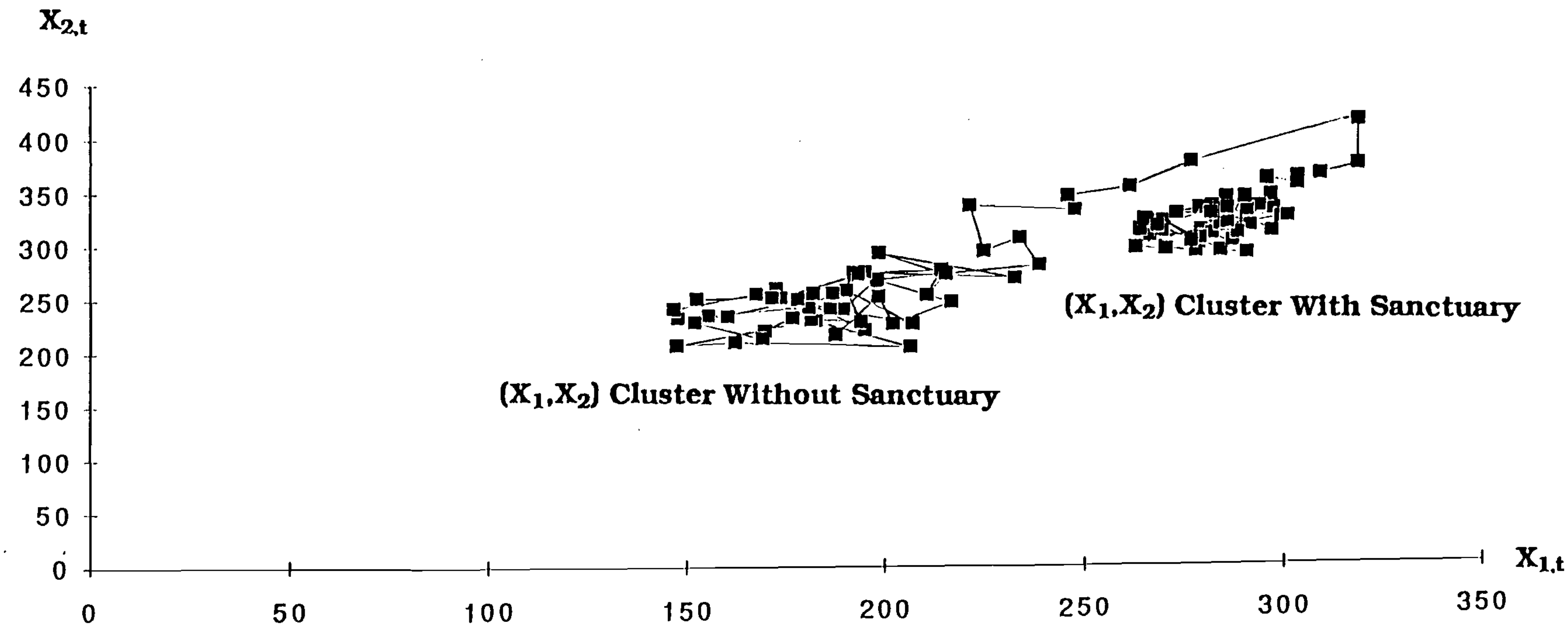
| Site | Size | Key Species or Historical/Cultural Significance |
|---|---|---|
| Channel Islands | 1,658 sq mi | California sea lion, elephant seal, blue whale, gray whale, dolphins, blue shark, brown pelican, western gull, abalone, garibaldi, rockfish. |
| Cordell Bank | 526 sq mi | krill, Pacific salmon, rockfish, humpback whale, blue whale, Dall's porpoise, albatross, shearwater. |
| Fragatelle Bay | 0.24 sq mi | tropical coral, crown-of-thorns starfish, blacktip shark, sturgeon fish, hawksbill turtle, parrot fish, giant clam. |
| Florida Keys | 3,674 sq mi | brain and star coral, sea fan, loggerhead sponge, tarpon, turtle grass, angelfish, spiny lobster, stone crab, grouper. |
| Flower Garden | 56 sq mi | brain and star coral, manta ray, hammerhead shark, loggerhead turtle. |
| Gray's Reef | 23 sq mi | northern right whale, loggerhead turtle, grouper, sea bass, angelfish, barrel sponge, ivory bush coral, sea whips. |
| Gulf of the Farallones | 1,225 sq mi | dungeness crab, gray whale, stellar sea lion, common murre, ashy storm petrel. |
| Hawaiian Islands Humpback Whale | 1,300 sq mi | humpback whale, pilot whale, monk seal, spinner dolphin, green sea turtle, trigger fish, cauliflower coral, limu. |
| Monitor | 0.79 sq mi | site of the wreck of the *USS Monitor.* |
| Monterey Bay | 5,328 sq mi | sea otter, gray whale, market squid, brown pelican, rockfish, giant kelp. |
| Olympic Coast | 3,310 sq mi | tufted puffin, bald eagle, northern sea otter, gray whale, Pacific salmon, dolphin |
| Stellwagen Bank | 842 sq mi | northern right whale, humpback whale, bluefin tuna, white-sided dolphin, storm petrel, northern gannet, Atlantic cod, winter flounder, sea scallop, northern lobster. |

*Source: http://www.nos.noaa.gov/ocrm/nmsp/*

**Table 2. The Bioeconomics of Marine Sanctuaries: The Deterministic Model**

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | Parameters | | | Fishing in Sanctuay | | | Stability: | $\lvert\lambda 1\rvert < 1, \lvert\lambda 2\rvert < 1$ |
| 2 | r1= | 0.379 | | X1= | 189.813907 | | a1,1= | 0.52238509 |
| 3 | K1= | 318 | | X2= | 249.796905 | | a1,2= | 0.24038462 |
| 4 | s= | 100 | | | | | a2,1= | 0.31446541 |
| 5 | r2= | 0.312 | | G1(X1,X2)= | 1.5266E-05 | | a2,2= | 0.63942003 |
| 6 | K2= | 416 | | G2(X1,X2)= | -1.6776E-05 | | | |
| 7 | c1= | 12.33 | | Sum of ABVs | 3.2043E-05 | | $\beta$ = | 1.16180512 |
| 8 | d1= | 0.0897 | | | | | $\gamma$ = | 0.25843084 |
| 9 | q1= | 0.00114 | | E1= | 47.5529656 | | | |
| 10 | v1= | 0.0555 | | T1= | 3.09930354 | | $\lambda 1$ = | 0.86200208 |
| 11 | f1= | 1.0318 | | Y1= | 29.3563074 | | $\lambda 2$ = | 0.29980304 |
| 12 | c2= | 16.417 | | E2= | 23.5491966 | | | |
| 13 | d2= | 0.0575 | | T2= | 5.72726858 | | | |
| 14 | q2= | 0.000975 | | Y2= | 30.7803221 | | | |
| 15 | v2= | 0.07848 | | D(X1,X2)= | -0.35742521 | | | |
| 16 | f2= | 2.0993 | | | | | | |
| 17 | p= | 1.95 | | | | | | |
| 18 | | | | No Fishing in Sanctuary | | | Stability: | $\lvert\lambda 1\rvert < 1, \lvert\lambda 2\rvert < 1$ |
| 19 | | | | X1= | 282.744769 | | a1,1= | 0.39057064 |
| 20 | | | | X2= | 320.45762 | | a1,2= | 0.24038462 |
| 21 | | | | | | | a2,1= | 0.31446541 |
| 22 | | | | G1(X1,X2)= | 9.5144E-06 | | a2,2= | 0.53342896 |
| 23 | | | | G2(X1,X2)= | 1.7459E-05 | | | |
| 24 | | | | Sum of ABS= | 2.6973E-05 | | $\beta$ = | 0.9239996 |
| 25 | | | | | | | $\gamma$ = | 0.13274904 |
| 26 | | | | E2= | 27.9517816 | | | |
| 27 | | | | T2= | 4.22367329 | | $\lambda 1$ = | 0.74606805 |
| 28 | | | | Y2= | 34.8433131 | | $\lambda 2$ = | 0.17793155 |
| 29 | | | | D(X1,X2)= | 11.8803678 | | | |

**Figure 1. A Phase Plane Plot of a Sample Realization With and Without Area One as a Sanctuary**



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