The California Rockfish Conservation Area and Groundfish Trawlers at Moss Landing Harbor

MICHAEL G. DALTON
California State University, Monterey Bay

STEPHEN RALSTON
National Marine Fisheries Service

Abstract   *This article uses a bioeconomic model and data for groundfish trawlers at Moss Landing Harbor in Central California to analyze effects of spatial closures that were implemented recently by West Coast fishery managers to reduce bycatch of overfished groundfish stocks. The model has a dynamic linear rational expectations structure, and estimates of its parameters exhibit spatial variation in microeconomic and ecological factors that affect decisions about where and when to fish. Test results show that variation in marginal costs of crowding externalities and biological rates of stock productivity are the most significant factors to consider in the spatial management of groundfish trawlers at Moss Landing.*

Key words   Bioeconomic models, rational expectations, spatial fisheries management, time-series analysis.

JEL Classification Codes C3, D8, Q2.

Introduction

The Pacific Fishery Management Council (PFMC) recently adopted depth-based restrictions on fishing effort to move fisheries out of the depth zones inhabited by bocaccio and other overfished rockfish species (PFMC 2003). Under standards of the Sustainable Fisheries Act (SFA), a stock is overfished if its abundance is less than 25% of virgin or unfished biomass. Bocaccio have been important in both com-

mercial and recreational fisheries of California, but current abundance may be as low as 2% of historical levels (Starr, Cope, and Kerr 2002). Bocaccio were declared overfished by the National Marine Fisheries Service (NMFS) in 1998 (MacCall and He 2002). The commercial groundfish trawl fishery has been a major source of mortality because bocaccio are bycatch for trawlers. In response, the PFMC closed the California Rockfish Conservation Area (CRCA) to trawling as part of a strategy to keep the fishery open, but drastically reduce bycatch of a few key overfished species, like bocaccio.

According to SFA standards, the best scientific estimates of fleet-wide mortality of bocaccio and other overfished stocks should not exceed caps prescribed by fishery managers in formal rebuilding plans. To verify that the CRCA and other closed areas along the West Coast are not exceeding these caps, fishery managers need realistic bycatch rate estimates for areas outside the protected zone. To predict fleet-wide bycatch, the PFMC recently began using bycatch rate estimates derived from a sample of vessels in the West Coast Observer Program, along with landings and other data from a census of fleet-wide activity in the Pacific Fisheries Information Network (PacFIN). The boundaries of the CRCA may be adjusted when new data become available to update estimates of bycatch rates, which happened recently. In addition, if the rebuilding caps on fishing mortality are exceeded, then fishery managers will need to adjust the CRCA's boundaries or make other regulatory changes.

If effort shifts are an important response by fishermen to spatial management, then adjustments to the CRCA could affect the spatial and temporal distribution of fishing effort outside its boundaries. Since bycatch rates often vary by area and season, estimates of the spatial and dynamic patterns of fishing effort outside of closed areas are needed to predict total bycatch and fishing mortality for an analysis of alternative policies and scenarios. Economic responses by fishermen to spatial management in alternative scenarios are likely to depend on changes in abundance and costs, including vessel crowding, in the open areas. However, these changes are a matter of uncertainty for fishery managers, who have almost no quantitative information on how effort shifts are influenced by bioeconomic factors to guide or support policy decisions. Similarly, vessel crowding is an effect that is frequently cited by fisheries economists to be a potentially important factor in spatial management, though little is known about the empirical significance of this cost in different fisheries.

Bioeconomic models are the traditional tools in fisheries economics for analyzing the microeconomic effects of management. However, most bioeconomic models do not have an econometric foundation or microeconomic structure to evaluate the strength of competing effects involved with spatial management. For example, even if overall landings were to increase as a result of spatial management, the fleet may incur additional costs from vessel movement and crowding, and how these additional costs offset benefits in any particular fishery is open to question. Geospatial differences between fishing areas may also be important. For example, stock dynamics can be linked to climatic processes or other factors that exhibit spatial variation (Mantua *et al*. 1997). Moreover, the dynamics of ex-vessel prices may be important for determining the range of areas that are profitable to fish.

The bioeconomic model in this article addresses several factors that may affect decisions about where and when to fish. The model is a spatial extension of earlier work (Rosenman 1986, 1987; Rosenman and Whiteman 1987; Dalton 2001). Our two-area representation of spatial management is similar to the approach taken in Holland and Brazee (1996). In addition, an econometric framework for estimation and hypothesis testing is a key feature of our model, which has a structure similar to other linear-quadratic rational expectations models. A framework for hypothesis

testing has been developed for these models to test the cross-equation parameter restrictions implied by rational expectations, for example Sargent (1978). Work in this article extends Sargent's framework to our bioeconomic model and develops maximum likelihood tests to test for significance of parameters and spatial relationships.

The empirical analysis in this article follows the current situation in the West Coast groundfish trawl fishery with an important case that contributes to understanding about fishermen's responses to spatial management. The case involves groundfish trawlers at the port of Moss Landing, California. This port is associated with a group of trawlers that have fished for the Dover sole-Thornyheads-Sablefish (DTS) complex in an area where bocaccio bycatch has been a problem. Fishing decisions analyzed are conditional on the choice of a specific port, and this choice could be an important response by fishermen to spatial management. The work by Smith and Wilen in this issue shows that choice of port is an important factor for the California urchin fishery, but addressing this additional level of decision-making is unfortunately beyond the scope of our work here.

Maximum likelihood estimates and test statistics for several spatial restrictions on the bioeconomic model are computed with PacFIN data on fishing effort and ex-vessel prices for the sample of Moss Landing trawlers. Estimates for the least spatially restricted version of the bioeconomic model exhibit interesting patterns in factors related to economics and ecology, including climate. Test results show the most significant spatial differences in the areas inside and outside of the CRCA for Moss Landing groundfish trawlers may be attributed to a set of the bioeconomic model's parameters that describe structural relationships between stock dynamics and revenue per unit effort in each area. Of perhaps greatest interest to economists, test results show the parameters that measure the external costs of vessel crowding belong in this spatially significant set.

Bioeconomic Model

The bioeconomic model is a two-area extension of the fisheries model with dynamic adjustment costs used in Dalton (2001). The model analyzes decisions of a representative trawl vessel operator in a fleet of identical vessels. The model treats stock abundance at the level of an individual vessel operator as an unobserved variable that represents the operator's true beliefs about stock size. Because the representative vessel operator assumption has not been tested, the model is restricted to a group of groundfish trawlers with similar capabilities and behavior that is conditional on a specific port. Conditional on the port, many factors may influence decisions about where and when to fish. The model below includes stock dynamics, ex-vessel prices, climate, and the costs of vessel crowding and movement.

Time is indexed by year t, a nonnegative integer. Let P_t denote an index of ex-vessel prices at Moss Landing in year t. The price index is a composite of prices received at Moss Landing that are relevant to decisions about where, when, and how intensively to fish. The index value $j = 1$ represents the area inside the CRCA, and $j = 2$ refers to the area outside of the CRCA. In each area j, let A_{jt} denote net revenue per unit effort (RPUE), let H_{jt} denote total fishing effort in hours, let N_{jt} denote abundance of the target species, and let X_{jt} be the addition to the stock from recruitment.

Recruitment depends on climate through sea surface temperature S_t, which is observable and stochastic, and an unobservable random factor in each area, Y_{jt}. The climate variable S_t is intended to represent El Niño-Southern Oscillation (ENSO) events, which have coast-wide effects (Mantua *et al.* 1997), and climate in the model does not vary by area. Let A_t, H_t, N_t, X_t, and Y_t denote the corresponding column vectors.

The operator E_t is the expectation of the adjacent expression conditional on the information set available to fishermen at time t, which contains all variables in the model dated t or earlier. Under the rational expectations hypothesis, the conditional expectations are interpreted as optimal predictors of date $t + j$ variables conditional on information at t. For empirical work, decision rules that are linear functions of elements in the information set are convenient. Optimal linear decision rules are obtained by replacing the conditional expectations operators in what follows with the corresponding linear least squares projections on the set of available information.

Given A_{jt}, individual fishing effort of h_{jt} produces net revenue $A_{jt}h_{jt}$. The RPUE coefficients A_{jt} depend on total fishing effort H_{jt}, local abundance of target species N_{jt}, ex-vessel prices P_t, and the marginal costs of supplying fishing effort $\overline{w}_j$, which is assumed to be constant. Individuals treat each A_{jt} exogenously and assume that variables determining RPUE are related by:

$$A_{jt} = (f_{0j} - \overline{w}_j) + f_{1j}H_{jt} + f_{2j}N_{jt} + f_{3j}P_t. \tag{1}$$

The f_{ij} are parameters that measure effects of different variables on RPUE. The parameter f_{1j} measures effects of crowding externalities among fishing vessels, f_{2j} measures effects of stock abundance, and f_{3j} measures effects of ex-vessel prices. Without loss of generality, the intercept term f_{0j} is reinterpreted below net of $\overline{w}_j$. The model has a linear stock-effort relationship for each area:

$$N_{jt} = g_{0j} + g_{1j}H_{jt} - g_{1j}g_{2j}H_{jt-1} + g_{2j}N_{jt-1} + X_{jt}. \tag{2}$$

The g_{ij} are parameters that measure effects on stock abundance. The parameter g_{1j} measures effects of fishing effort on stock abundance. The parameter g_{2j} measures the deterministic component of recruitment or net growth of births less natural mortality, and each $|g_{2j}| < 1$ is a necessary condition for stability of the bioeconomic model. The presence of lagged fishing effort with coefficient $g_{1j}g_{2j}$ in equation (2) is a technical convenience that is useful below. The stochastic component of recruitment depends on climate, and this relationship is measured by τ_j so that $X_{jt} = \tau_j S_t + Y_{jt}$.

To derive explicit decision rules from the bioeconomic model that can be represented as a system of linear stochastic difference equations, further assumptions on the stochastic processes in the model are needed. Sea surface temperatures are assumed to follow a first-order Markov process:

$$S_t = \rho S_{t-1} + \varepsilon_{st}. \tag{3}$$

The unobservable fluctuations in recruitment also follow a first-order Markov process:

$$Y_{jt} = \lambda_j Y_{jt-1} + \varepsilon_{y_jt}, \ j = 1, 2. \tag{4}$$

The bioeconomic model is closed by assuming that a first-order stochastic process that depends on sea surface temperatures generates ex-vessel prices:

$$P_t = \phi_0 + \phi_1 P_{t-1} + \phi_2 S_{t-1} + \varepsilon_{pt}. \tag{5}$$

The random variables ε_{it}, for $i = p, s, y_1$ and y_2, are assumed to be least squares residuals, each with finite variance and zero conditional mean $E_{t-1} \varepsilon_{it} = 0$. Although this specification allows arbitrary contemporaneous correlation between the ε_{it}, it does

rule out autocorrelation and other types of covariance at nonzero lags.

A positive definite diagonal matrix, R, with components $r_j > 0$, describes dynamic and spatial adjustment costs associated with changes in the allocation of fishing effort:

$$R = \begin{pmatrix} r_1 & 0 \\ 0 & r_2 \end{pmatrix}. \tag{6}$$

Let h_t denote the stacked column vector of fishing effort, h_{jt}, in each area $j = 1,2$. Vectors or matrices below with a prime denote the transpose operation. Restricting R to be a diagonal matrix omits the spatial adjustment cost term $(h_{1t} - h_{1t-1})'(h_{2t} - h_{2t-1})$, which could be significant, but omitting this term allows a convenient closed form factorization of the model's characteristic equation that is used to derive results. With R diagonal, adjustment costs at each t are:

$$K_t = \frac{r_1}{2}(h_{1t} - h_{1t-1})^2 + \frac{r_2}{2}(h_{2t} - h_{2t-1})^2. \tag{7}$$

The identical vessel operators have a common discount factor $0 < \beta < 1$. Given vectors of initial conditions in each area for fishing effort h_0 and stock abundance N_0, each operator chooses a sequence of random variables $\{h_t\}_{t=1}^{\infty}$ that solves:

$$\max \quad E\sum_{t=0}^{\infty} \beta^t \left(A_t \cdot h_t - \frac{1}{2}(h_t - h_{t-1})'R(h_t - h_{t-1}) \right) \tag{8}$$

$$\text{s.t.} \quad A_{jt} = f_{0j} + f_{1j}H_{jt} + f_{2j}N_{jt} + f_{3j}P_t$$

$$N_{jt} = g_{0j} + g_{1j}H_{jt} - g_{1j}g_{2j}H_{jt-1} + g_{2j}N_{jt-1} + X_{jt}.$$

Solutions to this maximization problem are vector functions that describe the dynamic and spatial allocation of fishing effort, and map elements of the model's underlying probability space to sequences of real vectors that describe fishing effort in each area. Functions that maximize equation (8) are characterized by first-order necessary conditions, or stochastic Euler equations, and a set of stochastic transversality conditions.

The Euler equations and transversality conditions are necessary and sufficient for maximizing the objective in equation (8). These conditions, and the derivation of the regression equations for the bioeconomic model, are described in Appendix A. The appendix defines scalars γ_{kj}, for $k = 1,2,3$, vectors θ_{pj} and θ_{sj}, and a vector of constants c in terms of the bioeconomic model's structural parameters β, f_{ij}, g_{ij}, r_j, ϕ_j, and ρ, for $i = 0,1,2$, and $j = 1,2$. For compact notation, define a column vector $q_t = (P_t, S_t)'$. Results in the appendix lead to a system of regression equations for fishing effort in each area under the hypothesis of rational expectations:

$$H_{jt} = c + (\gamma_{1j} + \gamma_{3j} + \lambda_j)H_{jt-1} - (\gamma_{1j}\gamma_{3j} + \gamma_{1j}\lambda_j + \gamma_{3j}\lambda_j)H_{jt-2} + \gamma_{1j}\gamma_{3j}\lambda_j H_{jt-3} \tag{9}$$

$$+ \left[\left(\frac{f_{3j}}{\beta r_j}\theta_{pj} + \frac{f_{2j}\tau_j}{\beta r_j}\theta_{sj} \right)(\Phi - \lambda_j I) - \frac{f_{3j}g_{2j}}{\beta r_j}\theta_{pj} \right]q_{t-1} + \frac{\lambda_j f_{3j}g_{2j}}{\beta r_j}\theta_{pj}q_{t-2} + U_{jt}.$$

These equations show the restrictions that optimizing behavior put on the bioeconomic model. By construction, $E_{t-1}U_{jt} = 0$ and the disturbance term U_{jt} in expression (9) is a forecast error that is optimal or rational in the sense of being uncorrelated with all information in the model dated $t - 1$ or earlier. The equations in (9) are the aggregated behavioral rules in a symmetric competitive equilibrium for the identical vessel operators conditional on the stochastic processes for ex-vessel prices and sea surface temperatures.

Data

Spatial data on fishing effort and ex-vessel prices from 1981–2001 for Moss Landing are from PacFIN.[1] Data on fishing effort are from California logbooks for groundfish trawlers. To control for heterogeneity among vessels and operators, the analysis focuses on a select group of fishing vessels, each with a limited entry groundfish trawl permit and DTS landings from fishing trips that departed from and returned to Moss Landing. In addition, each vessel in the group had tows with catch of DTS species recorded both inside and outside of what is now the CRCA. These conditions on the data require that selected vessels have demonstrated the capability of trawling in the deeper waters outside of the CRCA, and may feasibly shift effort there in response to the recent PFMC closures.

Total annual fishing effort inside and outside the CRCA is measured by the sum of annual tow hours for the selected vessels in each area from the PacFIN logbook data. Figure 1 shows the average distribution of trawl effort from 1981–2001 by the selected vessels. Increases in average trawl effort are represented in the figure by darker blocks, in increments of approximately 120 tow hours per year (hr/yr). The hatched blocks show the area inside the CRCA.[2]

The time series data used for analysis are plotted in figure 2. The plots show total annual tow hours in each area for the selected vessels. Total annual ex-vessel revenues and landings of DTS species for the selected vessels are computed from California fish tickets. Data on landings and ex-vessel revenues for the vessels are combined to form an index of real ex-vessel prices. Real revenues for each year are calculated with the Producer Price Index for crude foodstuff and feedstuff commodities from the Bureau of Labor Statistics. The annual index of real ex-vessel prices is

---

[1] A Compaq Evo N600c PC laptop, running Windows 2000 Professional performed all computational work in this article. Perl code was developed to search and sort the PacFIN data. ArcView 3.2 and ArcGIS 8.1 were used for GIS work. A Fortran program was used to compute annual average sea surface temperatures. Mathematica 4.2 produced all other empirical results, including parameter estimation and hypothesis testing for all regressions. Copies of the Perl code, the Fortran program, and the GIS work not subject to PacFIN confidentiality restrictions are available by request. The Mathematica code and time series data used for regressions are available at http://science.csumb.edu/~mdalton/MRE.

[2] Boundaries of the CRCA were published as coordinates of latitude and longitude in the Federal Register as part of the 2003 PFMC groundfish specifications. A GIS representation of the CRCA based on the original description in terms of depth contours was used because bathymetric data in a GIS format from California Department of Fish and Game (CDFG) facilitated this type of analysis. Spatial resolution of the California logbook data is constrained by the CDFG statistical fishing blocks that appear in figure 1. These blocks give an imprecise fit in a few places to the area between the depth contours that define the boundaries of the CRCA. In these cases, the smallest set of fishing blocks that completely covers the CRCA was used as an approximation, which tends to overestimate the size of the CRCA with the specifications used in this article. On the other hand, boundaries of the CRCA have been expanded beyond the specifications used in this article as part of in-season adjustments based on new information revealed at the April 2003 PFMC meeting. The new information, from the West Coast Observer Program, showed that bycatch of bocaccio was much higher than previously believed, by an order of magnitude in some cases. Incorporating the in-season adjustments to the CRCA, and sensitivity testing with different configurations of fishing blocks, are important tasks for future work.
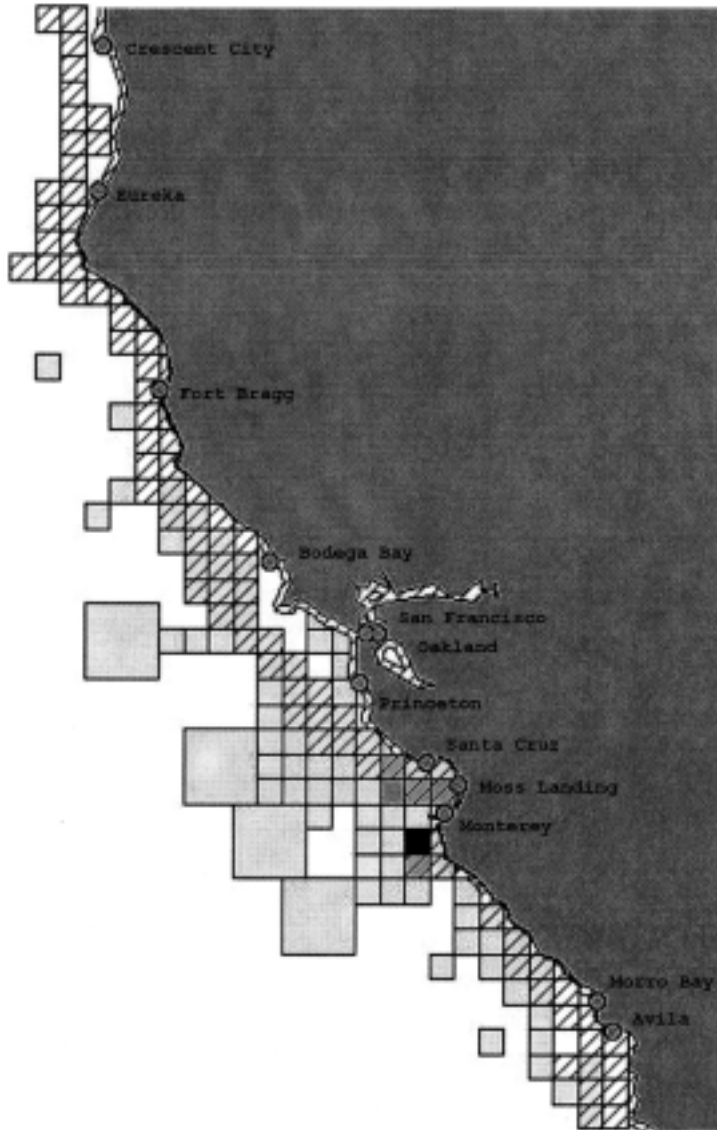
Figure 1. CRCA and Fishing Effort by DTS Trawlers at Moss Landing

computed by dividing total DTS real revenues by total DTS landings for the select group of vessels, and units of the price index are year 2000 dollars per pound ($ per lb.).

November-March average sea surface temperatures, measured in degrees Celsius (˚C), are computed from monthly sea surface temperatures observations from November 1981 through March 2002 in the electronic data library at Columbia University's International Research Institute (IRI) for Climate Prediction. The average sea surface temperatures are used as a local ENSO index that is described by Mantua *et al*. (1997). The figure shows annual values for this index, and the corresponding mean near Moss Landing.

Figure 2. Data for Fishing Effort, Ex-vessel Prices, and Climate

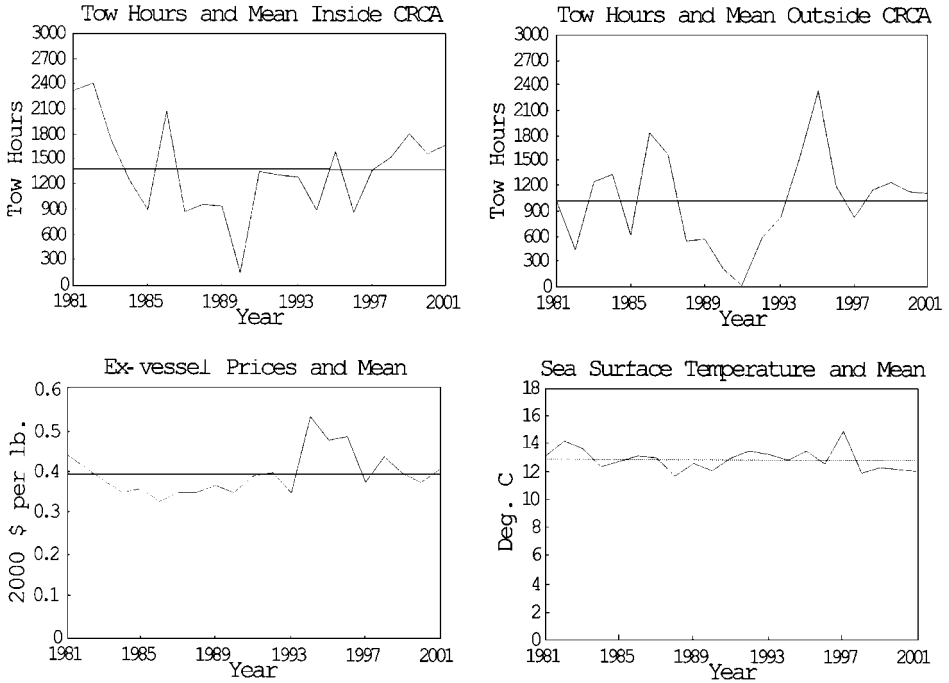To estimate parameters and compute test statistics for the bioeconomic model, the time series data on fishing effort, ex-vessel prices, and sea surface temperatures are first regressed on constants. The residuals from these regressions are normalized by corresponding values in 2001, the base year for estimation. The models used for all regressions are linear in variables, but not parameters, so the choice of base year does not affect results except to change units and normalize values. Use of the normalized residuals as data with the bioeconomic model simplifies work by allowing constants to be omitted from the regression equations. In addition, regressing on constants may limit the potential aggregation bias in the fishing effort data on total tow hours in each area. Results of eigenvalue tests, available upon request, show that normalized residuals for the system of fishing effort, ex-vessel prices, and sea surface temperatures are covariance stationary, and therefore appropriate for use with the bioeconomic model. Methods to estimate and test the model are described in Appendix B.

Results

This section reports maximum likelihood estimates and results of testing the bioeconomic model (3), (5), and (9). The discount factor is assumed to be $\beta = 0.95$ in all regressions. Since estimation of the model uses data that are differences from means, constant terms such as f_{0j}, g_{0j}, and ϕ_0 are dropped from the equations prior to estimation.

Table 1 presents maximum likelihood estimates for the bioeconomic model. The estimates have expected signs and satisfy conditions that are required for stability of the model. Estimates of f_{1j} measure effects of crowding externalities on RPUE inside and outside of the CRCA, or $j = 1,2$, respectively. Estimates of f_{2j} measure effects of stock abundance on RPUE. Estimates of f_{3j} measure effects of ex vessel prices on RPUE. Estimates of g_{1j} measure effects of fishing effort on stock abundance. Estimates of g_{2j} measure effects of lagged abundance on the stock, and absolute values of these estimates are less than one, and therefore satisfy stability conditions of the model. Estimates of the other parameters are also plausible, and indicate, for example, that ENSO events have negative effects on recruitment and abundance.

A vector autoregression (VAR), with the data in figure 2, is used as a null hypothesis for testing the parameter restrictions implied by rational expectations in the bioeconomic model. Specifically, the VAR used to test rational expectations has a triangular structure with sea surface temperatures related only to lagged sea surface temperatures; ex-vessel prices related to lagged ex-vessel prices and sea surface temperatures; and fishing effort in each area related to lagged fishing effort in both areas, ex-vessel prices, and sea surface temperatures.[3]

Table 2 presents covariance estimates and likelihood values for the bioeconomic model and the VAR alternative. The likelihood values are used to calculate likelihood ratio statistics for the asymptotic χ^2 or small sample tests that are described in Appendix B.[4]

Table 3 shows results from two tests of rational expectations, tests for spatial heterogeneity, and results of several other significance tests. The asymptotic and small sample tests fail to reject the restrictions associated with rational expectations in the bioeconomic model at a significance level of 5%, and other test results are judged relative to the least spatially restricted version of the bioeconomic model. In this case, the parameter restrictions are tested with asymptotic χ^2 statistics, and only results that are significance at the 5% level are presented. Results in the table are

Table 1
Parameter Estimates for the Bioeconomic Model

Parameter	Inside CRCA	Outside CRCA	Joint
f_1	−0.297	−0.284	
f_2	0.046	0.014	
f_3	0.177	0.237	
g_1	−0.012	−0.013	
g_2	−0.055	0.423	
r	0.26	0.092	
τ	0.047	0.006	
λ	−0.313	0.039	
ϕ_1			0.453
ϕ_2			0.049
ρ			−0.032

---

[3] Results of a diagnostic VAR analysis that tests significance and directions of Granger causality in the model are included in an appendix to this article that is available from the authors by request. The key results show that ex-vessel prices Granger cause fishing effort, but that fishing effort does not cause ex-vessel prices. These results are consistent with the assumption of exogenous prices in equation (8).
[4] Both test statistics have χ^2-distributions with degrees of freedom equal to the number of restrictions imposed by the bioeconomic model on the alternative VAR. The alternative VAR has 26 coefficients, and the bioeconomic model has 19 parameters, so both test statistics have seven degrees of freedom.

Table 2
Estimated Covariance and Likelihood Values

	Bioeconomic Model				Alternative VAR			
	H_1	H_2	P	S	H_1	H_2	P	S
H_1	1.906	4.263	−0.509	−0.218	1.377	2.629	−0.116	0.048
H_2		23.081	5.195	−1.124		19.279	7.508	−1.206
P			16.986	0.589			15.027	0.497
S				0.921				0.911
Likelihood				293.075				139.663

organized by tests for spatial differences and tests of significance. Both types of tests are applied first to associated pairs of parameters for each area, and then to related groups of parameters.

Discussion

The objective of the CRCA is to rebuild overfished groundfish stocks by eliminating fishing effort, and therefore bycatch, in the depth zones inhabited by overfished species such as bocaccio. Even with the CRCA, and other strict regulations, bocaccio mortality from trawlers will occur as a result of bycatch in other areas that could jeopardize success of the rebuilding plan for this stock. For example, estimates of bocaccio mortality by trawlers increased recently, by an order of magnitude in some cases, after new observer data on discard rates became available. With this new information, discussion by the PFMC and comments by commercial fishermen raised questions that shifted attention from bycatch rates to how changes in fishing effort from the recent closures, including the CRCA, were counted in the new estimates. Work in this article analyzes how the spatial distribution of fishing effort in areas inside and outside of the CRCA by groundfish trawlers at Moss Landing depends on effects of past effort, abundance, ex-vessel prices, and climate, and also how fishing effort depends on expectations about future values of these variables. Results of this analysis show how costs of vessel movement and crowding interact with changes in local abundance to affect the spatial and temporal distribution of fishing effort. The assumption of rational expectations in the bioeconomic model is used to identify estimates of the model's structural parameters. Tests of this assumption show that identifying restrictions implied by rational expectations in the bioeconomic model are acceptable.

Tests of the bioeconomic model under the assumption of rational expectations identify several significant spatial relationships between vessel crowding and stock dynamics. Externalities from vessel crowding are recognized by fisheries economists as a potentially important cost of spatial management, and may be an important consideration in deciding which areas to close. Our estimates of the marginal cost of vessel crowding inside and outside the CRCA are similar, though the difference is significant.

Results on spatial differences in the bioeconomic model show that parameters governing the deterministic component of stock dynamics are nonzero and have different signs inside and outside the CRCA. Estimates of these parameters are consistent with stability of the model. However, the negative estimate inside the

Table 3
Tests of the Bioeconomic Model

Test	Asymptotic χ^2		Small Sample	
	Stat.	Sig.	Stat.	Sig.
Rational Expectations	13.342	0.064	5.930	0.548
Spatial Restrictions on Pairs of Parameters				
$f_{11} = f_{12}$	10.553	0.001		
$g_{21} = g_{22}$	6.955	0.008		
$\lambda_1 = \lambda_2$	7.837	0.005		
Spatial Restrictions on Groups of Parameters				
$f_{11} = f_{12}$ and $g_{21} = g_{22}$	6.674	0.036		
$f_{21} = f_{22}$ and $g_{21} = g_{22}$	7.273	0.026		
$g_{11} = g_{12}$ and $g_{21} = g_{22}$	6.925	0.031		
Significance of Pairs and Groups of Parameters				
$f_{31} = f_{32} = 0$	7.019	0.030		
$g_{21} = g_{22}$	7.090	0.029		
$\lambda_1 = \lambda_2 = 0$	7.439	0.024		
$\phi_1 = 0$	11.799	0.001		
$\rho = 0$	5.858	0.016		
Significance of Groups of Parameters				
$f_{11} = f_{12} = f_{21} = f_{22} = 0$	15.519	0.004		
$f_{11} = f_{12} = f_{21} = f_{22} = f_{31} = f_{32} = 0$	19.300	0.004		

CRCA predicts that recovery dynamics, in the absence of fishing, will fluctuate above and below the long-run equilibrium value and that convergence to equilibrium will not be monotonic, which could confound rebuilding plans. On the other hand, the positive estimate outside the CRCA predicts that shifts in fishing effort from closing the CRCA will cause a monotonic decline in abundance to the long-run equilibrium associated with the new level of fishing effort. Oscillatory dynamics inside the CRCA may arise from reduced foraging competition.

The pattern of negative versus positive autocorrelation inside and outside of the CRCA, respectively, is repeated in the dynamics of the stochastic fluctuations in recruitment, and these spatial differences are also significant. Results also show that spatial differences in stock dynamics are linked to spatial differences in other key relationships described by the bioeconomic model including those involving vessel crowding, abundance and catch per unit effort, and effects of fishing effort on the stock. While spatial differences in estimates of vessel crowding and fishing mortality are comparatively small, effects of a given change in abundance on catch per unit effort are greater inside the CRCA.

While these results may give insight about spatial and dynamic effects of the CRCA on Moss Landing trawlers, restrictions on the bioeconomic model and important omitted factors in the analysis should be addressed before the type of approach

described in this article will be useful to fishery managers. Relaxing an important restriction on the covariance of dynamic adjustment costs in the bioeconomic model would allow the model to be used for predicting effort shifts from adjustments in the boundaries of the CRCA, and this development of the model is planned for future work. Additional spatial detail could be obtained by increasing the number of areas to more than two in the bioeconomic model, which will require additional development of the model and a new numerical approach.

Another priority for future work is to include trip limits and other regulatory instruments that are used to manage West Coast groundfish. Time series data on trip limits for groundfish trawlers in California have been compiled, and effects of these regulatory instruments will be incorporated into the bioeconomic model. Work on testing the assumption of identical vessels in the model is also proceeding, with interesting results, and future work with the bioeconomic model could incorporate heterogeneity among vessels. The framework for testing differences between vessels uses PacFIN data as a panel, and the choice of port could also be treated in this framework.

A bioeconomic model with these features could be used to analyze effects of spatial management and other regulations on fishermen's spatial and dynamic behavior, including effort shifts. The spatial and dynamic patterns of fishing effort predicted by this model could be coupled with discard rate estimates to identify cost-effective solutions in the model that satisfy constraints of the rebuilding plans for bocaccio and other overfished groundfish stocks.

References

Dalton, M.G. 2001. El Niño, Expectations, and Fishing Effort in Monterey Bay, California. *Journal of Environmental Economics and Management* 42(3):336–59.

Holland, D.S., and R.J. Brazee. 1996. Marine Reserves for Fisheries Management. *Marine Resource Economics* 11(3):157–71.

International Research Institute for Climate Prediction (http://iri.ldeo.columbia.edu).

MacCall, A., and X. He. 2002. Status Review of the Southern Stock of Bocaccio (*Sebastes paucispinis*) (http://noaa.gov/prot_res/readingrm/FRNotices/bocaccio_status_review.pdf).

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society* 78(6):1069–79.

PFMC. 2003. (www.pcouncil.org/groundfish/gfcurr.html#new), September 25.

Rosenman, R.E. 1986. The Optimal Tax for Maximum Economic Yield: Fishery Regulation under Rational Expectations. *Journal of Environmental Economics and Management* 13(4):348–62.

___. 1987. Structural Modeling of Expectations and Optimization in a Fishery. *Natural Resource Modeling* 2(2):245–58.

Rosenman, R.E., and C.H. Whiteman. 1987. Fishery Regulation under Rational Expectations and Costly Dynamic Adjustment. *Natural Resource Modeling* 1(2):297–320.

Sargent, T.J. 1978. Estimation of Dynamic Labor Demand Schedules under Rational Expectations. *Journal of Political Economy* 86(6):1009–44.

Starr, R.M., J.M. Cope, and L.A. Kerr. 2002. *Trends in Fisheries and Fishery Resources Associated with the Monterey Bay National Marine Sanctuary from 1981–2000.* La Jolla, CA: California Sea Grant College Pub. No. T-046.

Appendix A

Regression Equations

The stochastic Euler equations for the maximization problem in equation (8) are:

$$A_{1t} - r_1(h_{1t} - h_{1t-1}) + \beta r_1(E_t h_{1t+1} - h_{1t}) = 0$$
$$A_{2t} - r_2(h_{2t} - h_{2t-1}) + \beta r_2(E_t h_{2t+1} - h_{2t}) = 0,$$
(10)

and the stochastic transversality conditions are given by:

$$\lim_{T \to \infty} \beta^T E_t b_{jt+T} = 0, \, j = 1, 2.$$
(11)

Rearranging the Euler equations gives the system:

$$E_t h_{1t+1} - \frac{1+\beta}{\beta} h_{1t} + \frac{1}{\beta} h_{1t-1} = -\frac{1}{\beta r_1} A_{1t}$$
(12)

$$E_t h_{2t+1} - \frac{1+\beta}{\beta} h_{2t} + \frac{1}{\beta} h_{2t-1} = -\frac{1}{\beta r_2} A_{2t}.$$

In a symmetric competitive equilibrium, which is also a Nash equilibrium, $h_{jt} = H_{jt}$ for all j and t. Using the lag operator L and the 2×2 identity matrix I, the pair of dynamic equations can be expressed as:

$$(I - IL)\left(I - \frac{1}{\beta} IL\right)H_t = -\frac{1}{\beta} R^{-1}A_{t-1}.$$
(13)

Let f_0 and g_0 denote column vectors with components f_{0j} and g_{0j}, $j = 1,2$, respectively. Let F_i and G_i denote diagonal matrices with diagonal components given by f_{ij} and g_{ij}, for $i = 1,2$ and $j = 1,2$. Let Ψ denote the diagonal matrix with components $\Psi_{jj} = \tau_j$, $j = 1,2$. The G_i are diagonal and commute. The form for stock dynamics in equation (2) gives:

$$(I - G_2L)N_t = g_0 + G_1(I - G_2L)H_t + X_t.$$
(14)

The F_i are also diagonal and commute, allowing a substitution of fishing effort and environmental effects for stock dynamics in RPUE:

$$(I - G_2L)A_t = (I - G_2)f_0 + F_2g_0 + (F_1 + F_2G_1)(I - G_2L)H_t + F_3(I - G_2L)P_t + F_2X_t. \quad (15)$$

Since R is diagonal, so is R^{-1} and it commutes with G_2. Premultiply both sides of equation (13) by $(I - G_2L)$ and use the equation above to obtain:

$$(I - G_2L)(I - IL)\left(I - \frac{1}{\beta} L\right)H_t$$
(16)

$$= -\frac{1}{\beta} R^{-1}\left[(I - G_2)f_0 + F_2g_0 + (F_1 + F_2G_1)(I - G_2L)H_{t-1} + F_3(I - G_2L)P_{t-1} + F_2X_{t-1}\right].$$

Using the matrix determinant operator det($\cdot$) and collecting endogenous fishing effort variables H_t in the system above leads to a characteristic equation for this system in terms of a matrix polynomial:

$$\det\left\{(I - G_2 z)\left[I(1 - z)\left(1 - \frac{1}{\beta}z\right) + \frac{1}{\beta}R^{-1}(F_1 + F_2 G_1)z\right]\right\} = 0. \tag{17}$$

Under conditions assumed here, the matrix polynomial may be factored by matrices Γ_i, $i = 1,2,3$ so that:

$$\det\left[(I - \Gamma_1 z)(I - \Gamma_2 z)(I - \Gamma_3 z)\right] = 0. \tag{18}$$

Let $\Gamma_3 = G_2$ and the remaining quadratic factors satisfy:

$$\det\left\{I + \frac{1}{\beta}\left[-(1 + \beta)I + R^{-1}(F_1 + F_2 G_1)\right]z + \frac{1}{\beta}Iz^2\right\} = 0. \tag{19}$$

This equation may be simplified to:

$$\det\begin{bmatrix} 1 + \left(-\dfrac{1+\beta}{\beta} + \dfrac{f_{11}}{\beta r_1} + \dfrac{f_{21}g_{11}}{\beta r_1}\right)z + \dfrac{1}{\beta}z^2 & 0 \\[2mm] 0 & 1 + \left(-\dfrac{1+\beta}{\beta} + \dfrac{f_{12}}{\beta r_2} + \dfrac{f_{22}g_{12}}{\beta r_2}\right)z + \dfrac{1}{\beta}z^2 \end{bmatrix} = 0. \tag{20}$$

Since the determinant in this case is the product of diagonal terms, the characteristic polynomial is a partially factored fourth-order polynomial in the real or complex variable z. Let η_i denote the coefficient for z in each diagonal component. The characteristic equation may be expressed as:

$$\left(1 + \eta_1 z + \frac{1}{\beta}z^2\right)\left(1 + \eta_2 z + \frac{1}{\beta}z^2\right) = 0. \tag{21}$$

Components of the matrix factors Γ_1 and Γ_2 are obtained from the transformation $x = 1/z$:

$$\left(x^2 + \eta_1 x + \frac{1}{\beta}\right)\left(x^2 + \eta_2 x + \frac{1}{\beta}\right) = 0. \tag{22}$$

Use of the quadratic formula completes the factorization. Note that each pair $i = 1,2$ gives one stable and one unstable root. Collect the negative or stable roots in the first matrix factor:

$$\Gamma_1 = \frac{1}{2} \begin{pmatrix} -\eta_1 - \sqrt{\eta_1^2 - 4/\beta} & 0 \\ 0 & -\eta_2 - \sqrt{\eta_2^2 - 4/\beta} \end{pmatrix}. \tag{23}$$

Collect the positive or unstable roots in the second matrix factor:

$$\Gamma_2 = \frac{1}{2} \begin{pmatrix} -\eta_1 + \sqrt{\eta_1^2 - 4/\beta} & 0 \\ 0 & -\eta_2 + \sqrt{\eta_2^2 - 4/\beta} \end{pmatrix}. \tag{24}$$

The factored system is equivalent to:

$$(I - \Gamma_1 L)(I - \Gamma_2 L)(I - \Gamma_3 L) H_t \tag{25}$$

$$= -\frac{1}{\beta} R^{-1} \big[(I - G_2) f_0 + F_2 g_0 + F_3 (I - G_2 L) P_{t-1} + F_2 X_{t-1} \big].$$

The matrix factor Γ_2 is the unstable root that gives the forward solution:

$$(I - \Gamma_1 L)(I - \Gamma_3 L) H_t = -\frac{1}{\beta} R^{-1} \Big\{ (I - \Gamma_2)^{-1} \big[(I - G_2) f_0 + F_2 g_0 \big] \tag{26}$$

$$+ F_3 (I - G_2 L)(I - \Gamma_2 L)^{-1} P_{t-1} + F_2 (I - \Gamma_2 L)^{-1} (\Psi S_{t-1} + Y_{t-1}) \Big\}.$$

Let Λ denote the diagonal matrix with diagonal components λ_j, $j = 1,2$. A geometric formula and the Wiener-Kolmogorov least squares prediction formula applied to the last term on the right-hand side of the equation above implies:

$$(I - \Gamma_2 L)^{-1} Y_{t-1} = -\sum_{k=0}^{\infty} (\Gamma_2^{-1})^k E_t Y_{t+k} = -\sum_{k=0}^{\infty} (\Gamma_2^{-1} \Lambda)^k Y_t. \tag{27}$$

Let γ_{2j} denote the jth diagonal component of Γ_2. Then, $\sum_{k=0}^{\infty} (\Gamma_2^{-1} \Lambda)^k$ converges to a diagonal matrix with components $1/(1 - \lambda_j/\gamma_{2j})$. Denote the limit matrix by M_3. To compute forecasts for the other stochastic processes, define constants:

$$b_j = \frac{(1 - g_{2j}) f_{0j} + f_{2j} g_{0j}}{1 - \gamma_{21}}, \tag{28}$$

and express the equations in (26) explicitly:

$$(1 - \gamma_{1j} L)(1 - \gamma_{3j} L) H_{jt} \tag{29}$$

$$= -\frac{1}{\beta r_j} \Big\{ b_j + (1 - \gamma_{2j} L)^{-1} \big[f_{3j} (1 - g_{2j} L) P_{t-1} + f_{2j} \tau_j S_{t-1} + f_{2j} Y_{jt-1} \big] \Big\}.$$

Construct a transition matrix for the stacked system $q_t = (P_t, S_t)'$ from equations (3) and (5) so that:

$$\Phi = \begin{pmatrix} \phi_1 & \phi_2 \\ 0 & \rho \end{pmatrix}.$$ (30)

Stack the residuals in a column vector $\varepsilon_{qt} = (\varepsilon_{pt}, \varepsilon_{st})'$ and the transition equation for the stacked system is $q_t = \Phi q_{t-1} + \varepsilon_{qt}$. Factor $\Phi = JMJ^{-1}$. Assumptions made above require that P_t and S_t are of exponential order less than $1/\beta$, which implies the eigenvalues of Φ are also less than $1/\beta$ in absolute value. The matrix J contains the eigenvectors, and M is a diagonal matrix of eigenvalues for Φ. The factors give a k-step ahead least squares forecast of $E_t q_{t+k} = JM^k J^{-1} q_t$. Let $c_p = (1,0)$ and $c_s = (0,1)$. Note that:

$$(1 - \gamma_{2j}L)^{-1} P_{t-1} = -\sum_{k=0}^{\infty} \left(\frac{1}{\gamma_{2j}}\right)^k E_t P_{t+k} = -c_p \left[J \sum_{k=0}^{\infty} \left(\frac{1}{\gamma_{2j}} M\right)^k J^{-1} \right] q_t.$$ (31)

Similarly,

$$(1 - \gamma_{2j}L)^{-1} S_{t-1} = -\sum_{k=0}^{\infty} \left(\frac{1}{\gamma_{2j}}\right)^k E_t S_{t+k} = -c_s \left[J \sum_{k=0}^{\infty} \left(\frac{1}{\gamma_{2j}} M\right)^k J^{-1} \right] q_t.$$ (32)

The matrix series in equations (31) and (32) converge. To calculate the limits, let μ_i denote the eigenvalues of Φ, and for each $j = 1,2$, let M_j denote the diagonal matrix with diagonal components given by $1/(1 - \mu_i/\gamma_{2j})$, $i = 1,2,3$. Let $c_{y1} = (1,0)$, $c_{y2} = (0,1)$, and γ_{ij} denote the jth diagonal component of Γ_i. Define matrix coefficients:

$$\theta_{pj} = c_p (JM_j J^{-1})$$ (33)

$$\theta_{sj} = c_s (JM_j J^{-1})$$

$$\theta_{yj} = \frac{f_{2j}}{\beta r_j} c_{yj} M_3.$$

Substitute forecasts (27), (31), and (32) into (29) and rearrange terms to get:

$$H_{jt} = -\frac{b_j}{\beta r_j} + (\gamma_{1j} + \gamma_{3j}) H_{jt-1} - \gamma_{1j} \gamma_{3j} H_{jt-2}$$ (34)

$$+ \left(\frac{f_{3j}}{\beta r_j} \theta_{pj} + \frac{f_{2j} \tau_j}{\beta r_j} \theta_{sj} \right) q_t - \frac{f_{3j} g_{2j}}{\beta r_j} \theta_{pj} q_{t-1} + \theta_{yj} Y_{jt}.$$

Let $\tilde{Y}_{jt} = \theta_{yj}Y_{jt}$. Define zero conditional mean disturbance terms that are uncorrelated with past information:

$$U_{jt} = \left(\frac{f_{3j}}{\beta r_j} \theta_{pj} + \frac{f_{2j}\tau_j}{\beta r_j} \theta_{sj} \right) \varepsilon_{qt} + \tilde{Y}_{jt} - E_{t-1} \tilde{Y}_{jt}. \tag{35}$$

Note that $\theta_{pj}q_t = \theta_{pj}(\Phi q_{t-1} + \varepsilon_{qt})$ and $\theta_{sj}q_t = \theta_{sj}(\Phi q_{t-1} + \varepsilon_{qt})$. Redefine I to be the 3×3 identity matrix. Lag equation (34) and solve for $\tilde{Y}_{jt-1}$ to derive an expression for $E_{t-1} \tilde{Y}_{jt} = \lambda_j \tilde{Y}_{jt-1}$. Substitute this expression and the transition equation $q_t = \Phi q_{t-1} + \varepsilon_{qt}$ into equation (34) and collect terms to obtain the equations in (9).

Appendix B

Maximum Likelihood Estimation and Testing

Define a stacked vector of residuals for equations (3), (5), and (9) by $u'_t = (U_{1t}, U_{2t}, \varepsilon_{pt}, \varepsilon_{st})$. Assume that u_t has a multivariate normal distribution with zero mean $Eu_t = 0$, and finite covariance matrix $Eu_tu'_t = \Sigma$. The likelihood function for a sample of observations with residuals $\hat{u}_t$, $t = 1,\ldots,T$ is:

$$L = (2\pi)^{-\frac{3}{2}T}|\Sigma|^{\frac{1}{2}T} \exp\left(-\frac{1}{2} \sum_{t=1}^{T} \hat{u}'_t \Sigma^{-1} \hat{u}_t \right). \tag{36}$$

Following Sargent (1978), the maximum likelihood estimate of Σ is the sample covariance matrix:

$$\hat{\Sigma} = \frac{1}{T} \sum_{t=1}^{T} \hat{u}_t \hat{u}'_t. \tag{37}$$

Minimize the determinant of the covariance matrix $|\hat{\Sigma}|$ with respect to each of the model's parameters to obtain maximum likelihood estimates.

Let $\hat{\Omega}$ be the maximum likelihood estimate of Ω, the covariance matrix of an unrestricted third-order quadrivariate VAR, which is less constrained than the bioeconomic model. The likelihood ratio statistic defined by $T(\log|\hat{\Sigma}| - \log|\hat{\Omega}|)$ has an asymptotic χ^2 - distribution. The degrees of freedom for each statistic equals the number of restrictions imposed by the bioeconomic model on the unrestricted VAR. A small sample variation of these statistics replaces T, the number of data points in the sample after conditioning for lags, with $T - K$, where K is equal to the number of estimated parameters in each equation of the unrestricted VAR.