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Dynamic Spatial Heterogeneity and Habitat Protection: the Cost of Marine Protected Areas in the Gulf of Alaska

Matthew D. Berman, Edward J. Gregr,
and U. Rashid Sumaila

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email: matthew.berman@uaa.alaska.edu

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Matthew D. Berman
Institute of Social and Economic Research
University of Alaska Anchorage

Edward J. Gregr
U. Rashid Sumaila
Fisheries Centre
The University of British Columbia

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Address correspondence to: Matthew Berman, Institute of Social and Economic Research, University of Alaska Anchorage, 3211 Providence Drive, Anchorage, AK 99508 USA. (907) 786-5426, matthew.berman@uaa.alaska.edu.

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Abstract

Academics and fisheries managers are increasingly embracing spatial regulation, using mainly marine protected areas. Spatial heterogeneity challenges the ability of economic analysis to contribute to protected area design, especially where habitat quality may be linked to water column dynamics. We provide in this paper an experimental spatial evaluation approach that both identifies habitat quality and assesses opportunity costs of altered economic activities within protected area boundaries. Our approach accommodates spatial and temporal scales relevant to the underlying dynamic ecological and economic processes by linking them explicitly to a detailed spatial model of the marine physical environment. We apply this approach to estimate opportunity costs of curtailing commercial fisheries in a spatially complex system of protected areas in the Gulf of Alaska. The radical reduction in the spatial scale of analysis of fisheries decisions has direct applications to designing boundaries of marine protected areas and other spatial management decisions.

Key Words: Spatial valuation, marine ecosystems, fisheries management, marine protected areas, endangered species, Steller sea lion, Gulf of Alaska

Introduction

Until recently, most fisheries management regimes have relied on single species population models covering a large geographic area, usually limited only by the boundaries of a given regulatory jurisdiction. Recently, however, spatial management, using mainly marine protected areas, is increasingly being recognized as a necessity not only academically [14] [30] [13] but also for practical fisheries management.[1] Wilen [31] identified three key challenges that need to be understood and resolved in order to implement spatial fisheries management effectively: (i) better understanding of the determinants of fisher spatial behavior; (ii) better understanding of the interaction of economically driven effort dispersal with oceanographically driven biological dispersal; and (iii) the ability to provide *ex ante* evaluation of the implications of various potential spatial policy options. This paper addresses each of these challenges.

A key premise is that properly designed marine protected areas can maintain, and in some cases, increase fishery revenues [11]. Our objective here is to develop and test policy relevant research tools that can help fisheries managers design protected areas to achieve such benefits.[2]

Spatial heterogeneity of habitat quality provides both a challenge and an opportunity for designing a system of marine protected areas (MPAs) in a biological environment where resources are typically “patchy” [26]. Protecting such patches of high-quality habitat, or "hot-spots," may allow society to preserve much of the ecological value with only a relatively slight disruption to economic activities. Evaluating a system of protected areas involves both locating such patches and assessing opportunity costs of altered economic activities within them: activities that are often highly correlated with, if not directly dependent on the ecological values. A dynamic physical environment further challenges the design of MPAs, where seasonally variable surface heating and ocean currents interact with a fixed bathymetry to create mobile, spatially heterogeneous habitat patches.

We develop an experimental valuation approach that simply and flexibly accommodates the spatial and temporal scales of the underlying ecological and economic processes, by explicitly linking to a dynamic model of the physical environment. We apply that approach to estimate opportunity costs to commercial fisheries of a complex system of protected areas for Steller sea lions (*Eumetopias jubatus*) in the Gulf of Alaska [19]. We first summarize the modeling approach and place it in its theoretical context. We then describe the data available for linking fisheries with ecosystems in the Gulf of Alaska, and the statistical methods used for the empirical analysis. Next, we discuss estimation results for equations predicting spatial fish densities and the distribution of fishing effort. We use the results to produce spatially detailed estimates of economic values, with implications for the cost of habitat protection. We conclude with a discussion of the limits of the analysis and direction for future research.

Methods

In commercial fisheries, participants make repeated choices about what and where to fish [25]. This makes spatial discrete choice methods based on the Random Utility Model (RUM) [16] an appropriate approach for modeling spatial decisions of fishers and for evaluating opportunity costs of restricting fishing activities to accommodate new protected areas [28]. However, previous approaches to spatial choice in commercial fishing [4] [6] [12] have typically constructed choice sets from regulatory boundaries used for conservation and allocation among sectors of the fleet, or from arbitrary blocks of the ocean, rather than ecological information. Such an approach does not recognize that a large portion of the value of the regulatory area may be located in a small and potentially shifting portion of these larger zones. This has left these approaches with little ability to address either the dynamic ecological processes or the associated economic choices at a scale relevant to the evaluation of MPA design.

One problem is that information on spatial variation in habitat quality is rarely available. When such information has been available, it has typically been aggregated to a level that is too coarse for evaluating the effects of fishery closures within spatially complex reserve boundaries.[3] Estimating the cost to fisheries of habitat-based MPAs thus needs a new approach that recognizes the role of dynamic ecological processes in determining fishing location choice and analyzes them at the relevant scales. We propose an approach that radically downscales the analysis of fishing location choice analysis within a RUM framework, linking location decisions directly to environmental conditions at relatively fine spatial scales. Once we have estimated a set of equations that predict the value of habitat conditional on ecological and economic conditions, we then scale the analysis back up as needed to address the cost of closing fishing in protected areas.

The approach can, therefore, be seen as a test of two primary hypotheses:

1. Data on measured and modeled environmental variables can predict spatial variation in the density of catchable fish biomass at relatively small temporal and spatial scales, relevant to realistic modeling of fishing fleet choice sets, and management needs;

2. Resulting predictions of fish biomass, along with data on prices and indicators of fishing costs, can predict spatial choices of shore-based and offshore fishing fleets in a way that can be used to derive profit functions under the assumptions of RUM.

Theoretical approach

Our approach starts with a model of fishing fleet decision-making consistent with the assumptions of RUM. We extend RUM to address the goals of the project by making the following four additional assumptions:

1. Modeled alternatives are small geographic units with similar fish habitat;
2. Expected catch in each alternative unit depends on predicted fish density times geographic area;
3. Because alternatives are very small in relation to the total fishery area, the probability that any vessel uses a given area during each fishing day is small (generally < 1%);
4. One observes a large number of vessel-days per month in each modeled fishery (generally > 100).

Under these assumptions, the number of landings in an area during a specified time can be approximated by the Poisson probability distribution.[4]

Heterogeneity of fishers' risk preferences [17], along with heterogeneity of economic circumstances may interact with spatial heterogeneity (patchiness) of ecosystems.[5] Consequently, modeling heterogeneity is important for developing robust and realistic models of fishing behavior. Berman [3] described an approach for implementing the extension of RUM to commercial fisheries, consistent with the above four assumptions in a simple yet flexible way. Suppose that the utility that an agent in group *i* derives from selecting choice *j* at occasion *k*, is

$$U_{ijk,} = \alpha V_{ijk} + [\ \eta_{ijk} + \varepsilon_{ijk}\ ]\ , \tag{1}$$

where V_{ijk} represents the profit for alternative k, η_{ijk} is a random term with a zero mean whose distribution may be correlated with observed data, and ε_{ijk} is a random term with a zero mean with an independently and identically distributed with a type one extreme value distribution. The random variable η represents systematic but unobserved heterogeneity of operating costs, information, risk preferences, or other factors that might vary among vessels in the fishery. For a given value of η_{ijk}, the conditional probability π_{ijk} that a fisher from group i chooses area $j \in J_k$ is given by:

$$\log\pi_{ijk} = \alpha V_{ijk} + \eta_{ijk} - \gamma'_{ik}, \tag{2}$$

where

$$\gamma'_{ik} = \log\Sigma_{j\in Jk}\mathrm{e}^{\alpha V_{ijk} + \eta_{ijk}}. \tag{3}$$

Under the assumptions listed above, the conditional probability for the number of vessels y_{ijk} from group i observed fishing in area j during occasion k may be approximated by a poisson distribution:

$$\mathrm{prob}(y_{ijk} = y) = \lambda_{ijk}{}^{y}\exp(-\lambda_{ijk})/y!, \tag{4}$$

where

$$\lambda_{jk} = n_k\exp(x_{jk}\beta + \eta_{ijk} - \gamma'_k), \tag{5}$$

The unconditional probability distribution for y_{jk} depends on the distribution of η. However, equations (4) and (5) simply represent a form of "overdispersion" in the poisson model [5]. For example, if e^{η} is assumed to have a gamma distribution, the poisson approximation to the mixed logit becomes a negative binomial model, whose parameters can be estimated easily with conventional maximum likelihood.

Since the underlying choice probabilities conform to the assumptions of RUM, we may invoke RUM to estimate the conditional value of an area from the estimated parameters δ, ε, and g_k [27]. Given that the vessel has chosen to take a fishing trip under a given set of market and geospatial conditions, the difference in value between two subsets J_{1k} and J_{2k} of the choice set J_k is related to the parameter γ'_{ik}:

$$S_{J1k} - S_{J2k} = -(n_k/\alpha)\log\Sigma_{j\in J1k}\, e^{\alpha V_{ijk} + \eta_{ijk}}. - -(n_k/\alpha)\log\Sigma_{j\in J2k} e^{\alpha V_{ijk} + \eta_{ijk}}. \quad (6)$$

The opportunity cost of closing area j to fishing during choice occasion k reduces to:

$$-n_k \log[1/(1-\pi_{jk})]/\alpha. \quad (7)$$

Since the expected value of $\eta_{ijk} = 0$, a point estimate of the opportunity cost may be derived by evaluating the coefficients of a negative binomial regression for equation (2). However, the complexities for the derivation of welfare estimates with mixed logit models [8] apply here as well. In general, bootstrapping is necessary to generate confidence intervals around the point estimate.

Data sources

The North Pacific groundfish fishery is the largest industrial fishery in the United States, generating about $1 billion in *ex vessel* value and supporting seasonal employment of 12,000 workers on the largely Seattle-based fleet, and in shore-based processing plants in Alaska [18]. Gulf of Alaska fisheries typically account for about 15 percent of the total annual North Pacific groundfish revenues. Major commercial species in the trawl fisheries include Pacific cod, walleye pollock, and several species of flatfish and rockfish (*sebastes* spp.). Longline fisheries for halibut and black cod (sablefish) are managed separately under an individual transferable quota (ITQ) program. However, about one-third of the black cod quota is set aside for bycatch by trawl fishing vessels, which can be retained and sold. The longline fleet, composed primarily of smaller vessels, also fishes for Pacific cod. The focus of our analysis is on the larger trawl fisheries.

Primary data sources for the analysis consist of environmental indicators, data on fish catch and effort, data on fisheries openings and habitat regulations, and indicators of prices and costs. Environmental indicators included measured bathymetry, remote-sensed data, and oceanographic model output. Data sources on fish biomass density and fishing effort also provide limited additional environmental measurements, as described below.

Environmental indicators. We obtained remote-sensing data as monthly climatologies for four separate indicators: sea surface temperature, sea surface height anomaly, wind, and chlorophyll-a. Several different conditions could affect measured sea surface height, including salinity, temperature, and persistent atmospheric pressure anomalies, all of which could indicate habitat variation. Wind, inferred from satellite readings of wave height, indicates surface mixing and could be an important indicator of nutrient cycling. Chlorophyll-a measures primary production.

Al Hermann and Dave Musgrave provided detailed output from a Regional Ocean Modeling System (ROMS) model developed for the Gulf of Alaska [10] [9]. Model outputs were provided at a 3x3 km resolution, summarized as 2-week averages, for all of calendar year 2001. ROMS model indicators include temperature, salinity, and velocity vectors in each of three directions at multiple vertical levels. In addition, the model calculated a mixed layer depth and sea surface height anomaly. For the statistical analyses, we summarized the ROMS output by selecting data from three model levels: surface, bottom, and the level immediately below the calculated mixed layer depth. We calculated horizontal velocity from the orthogonal vector velocities. To reduce collinearity of variables at different depths, we represented the top and bottom layers as differences from the level below the mixed layer.

Each of the three types of environmental indicators has advantages and disadvantages. The ROMS output has the ability to "see" the ocean in three dimensions, as well as infer ocean dynamics through currents and eddies. However, it is difficult to validate the model to assess its accuracy at the fine scale we used.[6] The ROMS model coverage excludes a portion of the western Gulf of Alaska. Remote-sensing data provide direct measurements of dynamic environmental conditions. However, each of the remote-sensing indicators has separate issues limiting data quality, resolution, and interpretation.[7]

In order to model realistic behavioral choices of fishing fleets and address the complex spatial boundaries of protected areas considered in fishery management, we aimed for the finest spatial resolution possible, limited by the accurate resolution of the data available for analysis. We selected a 3x3 km rectangular grid based in large part on the resolution of the oceanographic model output. The area contained within the study area inside the U.S. Exclusive Economic Zone contains about 36,000 3x3 km cells.[8]

Bathymetry data were available from NOAA at the finest (3km) resolution. We generated slopes (rates of change across space) for bathymetry, using the formula (where

S represents slope, D represents bottom depth, and subscripts n, s, e, w denote the adjacent cells to the north , south, east and west, respectively):[9]

$$S = (180/3.14159)*\arctan\{ [((D_n-D_s)/2)^2 + ((D_w-D_e)/2)^2]^{1/2} \}. \qquad (8)$$

Fish density and fishing effort. Alaska Fisheries Science Center personnel kindly provided NMFS trawl biomass survey data for the Gulf of Alaska in 2001 [1], which we used to derive spatial estimates of fish densities. NMFS uses the survey for area-wide stock assessment. However, the survey records represent all species caught in each of 521 individual trawl hauls, providing spatial variation in CPUE.[10] 415 survey data points that lie within the ROMS study area.[11] In addition to haul weight by species and haul duration, each haul also records time and location, surface temperature and gear temperature.

The primary data source on fishery catch and effort consisted of individual haul records derived from the NMFS fisheries observer program. This program samples about 30 percent of all groundfish hauls in the Gulf of Alaska. Observer data include all gears and species harvested. For 2001, approximately 4,200 hauls were observed (about two-thirds representing onshore landings and one-third offshore). Most observed hauls include bottom depth, fishing depth, time, and location.[12] We joined the different data sets spatially by placing the 2001 survey and observer trawl ending locations and dates into the ROMS model grid (Figure 1). We averaged the fisheries data to match our two-week temporal resolution.

Fisheries openings and habitat regulations. Information on fishing seasons, and in-season time and area closures by gear and sector (onshore vs. offshore where different) were derived from public sources [20] [21]. The primary spatial management unit of most

NMFS in-season fisheries regulations is the three-digit management area. We also obtained information on seasonal time and area closures and gear restrictions related to bycatch, marine protected areas, and other environmental regulations from applicable sections of the Code of Federal Regulations archived on the NMFS Alaska region website [22]. NMFS staff provided digital spatial data delimiting the geographic boundaries for each separate environmental regulation. In all, we compiled 78 separate geographic areas, each applying to different gears, fisheries, and time periods. We interpolated where necessary to address spatial and temporal overlap between closure orders and the modeled spatial grid cells and time periods.

Indicators of prices and costs. Primary economic factors consisted of prices of targeted fish species and the distance traveled to access fishing areas. Ex vessel prices for trawl and fixed gear landings in the Gulf of Alaska and Bering Sea were obtained from [2]. For all fisheries, we calculated distance-to-port as the one-way distance from the harvest grid cell to the grid cell of the nearest of eight ports used by trawl fishing vessels, as reported to the Alaska Department of Fish and Game.[13]

Distance to port is not an important cost factor for GOA vessels that process fish on board the vessel, but travel cost between hauls remains relevant. Distance between consecutive offshore hauls theoretically measures travel cost. However, this is of little practical value, because even if one could construct a separate choice set for each grid cell where a haul is observed (since that cell becomes the starting point from which to measure distance to the next haul), knowing that a cell was selected because it was close to a previous haul location provides little useful information for spatial valuation. One could model the set of consecutive hauls in a nested choice framework. However, with dozens of consecutive hauls during a fishery, and with thousands of choices for each haul, the likelihood function would be infeasible to compute, even if one could construct the data set of inclusive values.[14] Given these challenges, we experimented with a simple approach that addressed travel distance conceptually in a nested model in a way that was easy to understand and straightforward to estimate. We hypothesized that the inclusive value at each stage (haul) was a function of CPUE, the distance to a subsequent haul, and the subsequent haul's inclusive value. If travel distance between hauls is typically low, a measure of average CPUE in the neighborhood around the grid cell in question will capture much of the variance in inclusive value.

In the hauls observed from the North Pacific trawl fisheries in 2001, travel distance between hauls was less than 30 km about 80 percent of the time. We constructed a measure of rockfish neighborhood CPUE that was a simple average of the predicted CPUE of all grid cells within 30km of each cell. Cells within this range that were on land or otherwise unavailable for fishing -- for example, with water depths deeper than 600 meters -- were included in the average with a zero value.

Statistical methods

Statistical analysis proceeded in two steps. First we estimated censored normal (tobit) regression equations explaining the spatial distribution of survey CPUE at each time step, as a function of the environmental variables. For all CPUE equations, we obtained a large improvement in the statistical fit by using a loglinear specification. We used the coefficients to project variation in expected CPUE over the entire study area.

Second, we estimated poisson and negative binomial regressions explaining the spatial distribution of fishing effort at each time step as a function of projected CPUE and economic factors, to obtain a set of spatial profit functions. We used the coefficients from the spatial profit functions to estimate the opportunity cost to each fishery of closing each individual 3x3 km grid cell -- or any combination of grid cells -- to fishing during a given two-week interval.

Estimation Results

Spatial fish density

The trawl survey is a spatially random sample taken during a relatively brief (approximately 2-month) time period, thus estimating CPUE is straightforward.[15] Table 1 contains the precise definition of variables included in the CPUE analysis using the survey data. The dependent variable is the natural logarithm plus one of CPUE, defined as total round weight for each species divided by trawl duration (kg/hour). Species considered included pollock, Pacific cod, black cod, and flatfish and rockfish species aggregated into two species groups. These represent the main target and bycatch fisheries for groundfish vessels in the GOA [2]. We considered only hauls with average weights of a given commercial species above a set of minimum thresholds, derived from the distribution of average fish weights in hauls for each species or species group, to represent aggregations of fish with likely commercial value. We estimated separate equations with and without wind. Since wind data were available for only about two-thirds of the observations, we decided to use tobit equations estimated without wind for CPUE predictions (Table 2).

Due to high collinearity between the set of modeled and observed environmental variables, and to increase robustness of the predictions, we dropped variables with a probability > 0.3 (absolute value of *t* statistic approximately equal to 1) from the equations. With separate intercepts for each time period, coefficients should be interpreted as effects of spatial anomalies; that is, deviations from the respective time-period mean.

The equations fit best for black cod and rockfish, and least well for Pacific cod. In general, the equations show a different pattern of significant variables across species, suggesting habitat selection. Several modeled environmental variables such as salinity, temperature at depth and velocity have significant estimated effects for each species, confirming that the ROMS model provided a significant contribution to the spatial predictions of CPUE at the scale of the study.

Spatial distribution of effort

In the second stage of the statistical analysis, we derived a profit function -- that is, a relationship for V_{ijk} in equation (2) -- based on associating the spatial distribution of observed fishing effort with a set of factors representing spatial variation in fishing costs and revenues. The geographic coverage of the ROMS model limited the spatial extent of CPUE predictions that relied on the model output. We also limited the choice set to the bottom depths included in the survey (less than 600 meters). This approximates the deepest trawl haul observed in the GOA fisheries.

The time frame for the survey data collection also limits the analyses. The 2001 survey was taken during the summer months -- late May through late July. The only groundfish trawl fisheries open for a large portion of the survey period were flatfish fisheries. Rockfish trawling was allowed during a three-week period in July. To estimate equations relevant to the pollock and Pacific cod trawl fisheries -- the largest GOA fisheries – we had to project the CPUE equations past the end of the range of the data used to estimate those relationships. We hypothesized that the relationship of the environmental variables to CPUE estimated during the survey period held for the period during which trawl fishing occurred in 2001 (late August to late October).[16]

Generating predictions for the entire Gulf of Alaska involved projecting outside the range of data observed in the 415 survey locations. This can be considered a problem of boundary conditions, such as in estuaries and other extreme marine environments. The problem is magnified by the fact that the CPUE equations estimated as loglinear equations generated exponential errors. One way of handling the data range problem is to limit the CPUE predictions to the range of the observations on the independent variables within the sampled points. This approach would be appropriate for handling out-of-sample prediction within the time horizon of the survey data set. Unfortunately, such an approach becomes problematic when extending predictions over time, because the ranges of the variables change seasonally.

We opted instead to censor a small percentage of high CPUE predictions. In essence, this approach assumed that the CPUE equations generated good predictions of suitable habitat, but cannot predict high abundance locations within that habitat. The rationale was based on the scale of spatial aggregations of fish compared to the spatial scale of the data: within any grid cell, we can expect that the survey will find the species present in significant numbers if environmental conditions favor it, but will only randomly find large aggregations that might be present nearby. The fishery, on the other hand, can search for locally for such aggregations.

Shore-based fisheries. We determined the appropriate censoring limits using a stepwise process based on the log likelihood of the equation for the distribution of fishing effort. We reduced the upper limit of predicted CPUE by one integer level of predicted log of CPUE at a time, until the log likelihood stopped increasing. This occurred at a value of 7 for pollock, and 3 for Pacific cod. This approach generated reasonable results for the profit functions, estimated as negative binomial regressions, for the distribution of shore-based pollock and Pacific cod trawl fishing effort (Table 3).

Since average CPUE changed for each time period -- fisheries and habitat regulations often changed as well -- a separate intercept term was included for each time period to represent the overall value of fishing opportunities during the period: the parameter γ'_k in equation (5). The constant term represents the intercept for model period 19 (August 23-September 5), the first summer period during which any landings were recorded for either fishery. Coefficients for the other periods represent effects relative to period 19. Pacific cod trawling occurred in the GOA in period 19, but was closed for the duration of period 21. Fishing ended for both fisheries on October 31 (period 23).

The negative binomial equations (Table 3) exhibit a high degree of dispersion: the variance scale factor is around 100 times the mean. This high variance created convergence problems for the algorithm, as small changes in the scale factor had little effect on the log likelihood or the other equation coefficients.[17] Nevertheless, the resulting equations for both pollock and Pacific cod appear reasonable. The coefficients on expected censored CPUE are positive and significant, and the coefficients on distance to port are significant and negative. The coefficients on the regulatory variables -- the fraction of the time included in a fishery opening and the fraction of the time subject to a habitat closure, respectively -- have the expected signs and are highly significant.[18]

GOA trawl fisheries directed at species besides pollock and Pacific cod include rockfish and flatfish fisheries, which are covered under a diverse set of regulations. A distinguishing characteristic of these fisheries is the dependence on retained bycatch for valuable species -- primarily black cod, but also rockfish for some vessels when the directed fishery is closed -- for additional revenue. For the shore-based fishery in particular, it is often difficult to determine the target species for a given vessel from the haul composition. Consequently, we estimated a single equation for "other" mixed trawl fisheries.

The best-fitting negative binomial regressions for fishing effort estimated for “other” trawl fisheries (Table 3) showed that the distribution of large rockfish, black cod, and flatfish all significantly predict location choice. Using the same censoring procedure as before, a censor of 3 for rockfish, 4 for flatfish and black cod, and 6 for pollock achieve the best fit. The constant term represents period 12. Port distance is again negative and highly significant, with a magnitude similar to the distance coefficients estimated for the other two shore-based fisheries. The negative and significant coefficient on pollock is not surprising, given that this species is abundant in the GOA, but, generally of lower commercial value.

Offshore fisheries. All GOA pollock is allocated to the shore-based sector, and too little Pacific cod is allocated to the offshore sector to estimate a location choice equation. However, a number of trawl catcher-processors prosecuted the mixed “other” fisheries in 2001. During the period in summer that rockfish was permitted as a target species (model periods 15 and 16), 279 hauls were observed: enough to estimate a choice equation for offshore fishing effort. Although the primary target for most of these hauls appears to have been rockfish, black cod, which has a high market value, remained an important bycatch species.

The results of estimating the negative binomial equation for spatial choice for the GOA offshore trawl fishery appear reasonable (Table 3). The coefficients on rockfish CPUE, black cod bycatch, and the rockfish neighborhood CPUE are all positive and significant. The constant term for the offshore fishery represents period 15; the intercept for period 16 represents an effect relative to period 15. The censoring procedure produced the highest log likelihood at a value of 4 for the natural log of rockfish CPUE, 8 for black cod, and 3 for the 30 km rockfish neighborhood CPUE.

Spatial values and the cost of habitat protection

Habitat protection for Steller sea lions in the North Pacific

The Steller sea lion (SSL) (*Eumetopias jubatus*), the largest eared seal (*Otariid*), ranges across the North Pacific coast from northern Japan to central California. Based on genetic differences, the species has been divided into two populations -- an Eastern and a Western stock -- at 144º W longitude, near Cape Suckling in the central Gulf of Alaska. Starting in the late 1970s, the western population began a precipitous decline. The decline coincided with a sharp increase in commercial fishing in the North Pacific after the United States created its Exclusive Economic Zone (EEZ) in 1976. The western stock is believed to rely for food on the main species targeted by the commercial fisheries [23].

In response to extended litigation by environmental groups, NMFS listed the western population of SSLs under the Endangered Species Act in 1996 and designated Critical Habitat within 20 nm of 39 rookeries and 83 haulouts, and inside three foraging areas.[19] The following year, NMFS issued a Biological Opinion that concluded that the groundfish fisheries jeopardized recovery of the species [24]. Designation of SSL Critical Habitat for in the North Pacific added dozens of small MPAs with complex spatial boundaries to an already complex regulatory regime to protect non-target species. Many of these areas overlap with areas traditionally exploited by the commercial fisheries for Pacific cod, pollock, and other groundfish species [19].

Opportunity cost to GOA trawl fisheries

Since the North Pacific groundfish trawl fisheries are regulated under a total allowable catch (TAC) regime, habitat closures are unlikely to be affect total harvests, market value, and gross revenues substantially. Expansion or contraction of spatial fishing opportunities would likely result in only a slight change in the number of hauls made by the fleet during the year. Instead, there would be a redistribution of a fixed level of fishing effort and catch among available fishing locations. Nevertheless, displacement from the new protected areas may impose real costs on the fishery from factors such as higher travel costs and lower catch rates. Consequently, we focused on estimated changes in the value per haul.

In order to assess the impact of the SSL MPAs, we first needed a baseline for comparison. The equations for fishing location choice were estimated based on the fisheries openings and habitat closures in effect during summer 2001On June 10, the congressionally mandated delay in implementing the judicial order expired, causing a shutdown of pollock and cod fishing in the GOA. The fisheries were reopened on July 17, when NMFS completed new regulations to comply with the order. To address this moving baseline, we estimated spatial relative values by evaluating equations (6) and (7) under the assumption that fishery TAC and bycatch regulations remained the same as in 2001, but that all spatial SSL regulations were removed. Removing the MPA restrictions inflates estimates of the total value of the fishery above that actually realized, but it provides a constant baseline from which to compare changes in *relative value* caused by introducing the MPAs.

The estimated baseline net value of summer trawl fishing in the Gulf of Alaska in 2001 (Table 4) therefore assumed that all SSL Critical Habitat closures were removed but that overall fishery openings remained in place. To scale the values, we first multiplied the results of equation (6) by the ratio of average target species catch in fishery hauls to predicted survey CPUE in the grid cells where hauls were observed. This adjusted for the difference between survey and expected fishery CPUE. We then multiplied by average ex-vessel prices to convert the units from tons of fish per haul to dollars per haul. Finally, we scaled up to total fishery value by multiplying the result for each month by the number of hauls observed during that month in summer 2001, divided by the estimated percentage of hauls in the GOA sampled by observers.[20] Figure 2 illustrates the detailed spatial variation of these value estimates for the Pacific cod shore-based trawl fishery, along with the applicable SSL MPA boundaries.

We estimated the opportunity cost to the summer and fall 2001 fisheries of the SSL regime that came into effect on July 17 by evaluating equation (6) with J_{1k} representing the choice set that would have been available if fishing had been permitted within the

SSL MPAs, and J_{2k} the choice set actually available for each fishery and time period. The estimated cost for Pacific cod shore-based trawl fishery was quite large: one-third of the potential value, or about $1,800 per haul (Table 4). The estimated cost for the pollock fishery was about half as great in dollar terms, but still substantial at 28 percent of potential value. These are the two main fisheries affected by the SSL closures. The estimated costs for the “other” mixed onshore and offshore trawl fisheries were slight: 0.2 percent of the potential value (Table 4). The SSL regulations closed relatively small areas of the Gulf of Alaska to these fisheries, and those areas -- such as 3 nm no-fishing zones around SSL rookeries and haulouts -- were of relatively little importance to these fisheries.

Our spatially detailed analysis provides an opportunity to measure the change in the cost to the fisheries of relatively small changes in the boundaries to the closed areas. We illustrate the capabilities of the method by applying it to an example. The Chiniak Gully research area (Figure 2) is a relatively small area off Kodiak that NMFS closed to all trawl fishing during the month of August 2001 for localized depletion research. We estimated the cost of the August 2001 research trawl closure, using the same methods as before, measured as the cost per haul averaged over the applicable two-week study time periods when the respective fishery was open. Again, the estimated cost was highest for the Pacific cod fishery: one percent of total value during that time period or nearly $200 per haul (Table 5). The closed area was estimated to be highly profitable for the Pacific cod trawl fishery because it had high expected CPUE and was close to the major fishing port of Kodiak. The cost to the pollock fishery was also one percent of value, but less in dollar terms. The money cost for the “other” shore-based trawl fisheries was even higher, but only about one-third as much in percentage terms. Since rockfish, the main offshore trawl target fishery in the Chiniak Gully area, was closed in the GOA during the research period, and the trawl sablefish bycatch allowance had also been reached, the cost for the offshore fisheries was presumably negligible.

Conclusions

In this study, we developed and tested an approach for estimating spatial values of ocean fisheries at fine spatial scales. The proposed approach provides one tool that can help move fisheries management from single-species population models covering a large geographic area, to spatial marine ecosystem management at fine scales. The two general hypotheses -- that environmental conditions explain and can predict the spatial distribution of fish density, and that predicted spatial fish densities predict the distribution of fishing effort at fine spatial scales -- received strong empirical support.

The application of the approach to estimate the cost to the North Pacific groundfish fisheries of a spatially complex system of MPAs to protect endangered SSLs generated plausible results. The estimated costs varied widely for different sectors of the trawl fleet, ranging from a loss of one-fourth to one-third of seasonal profits for pollock and Pacific cod catcher boats, to negligible for other onshore trawl fisheries and for rockfish catcher-processors. The analytical methods developed here could be applied directly in a management context to estimate the costs and benefits of proposed regulatory changes that involve time and area closures for the groundfish fleet. The analysis of the Chiniak Gully research closure provided one example of the kind of management information that the approach can provide.

A limitation of the approach is the challenge of estimating confidence intervals. In this case, bootstrapping would be very cumbersome for what is essentially a three-stage statistical procedure. Since our goal was to demonstrate the method rather than derive numerically precise values, we did not attempt such a computationally complex procedure to generate confidence intervals, and leave this for further research.[21] A much bigger source of uncertainty in the estimates derives simply from uncertainty in the predictions of spatial variation in CPUE. Thus, further work to improve the ability to explain and predict distribution of fish densities at fine spatial scales should have priority for increasing the practical benefits of the approach for spatial fisheries management.

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Endnotes

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[1] The latter has resulted in the creation of big efforts such as the Marine Managed Areas research and management program created by the environmental NGO Conservation International, and supported by the Gordon and Betty Moore Foundation (http://science.conservation.org/portal/server.pt?open=512&objID=469&&PageID=126248&mode=2&in_hi_userid=124186&cached=true).

[2] Of course, closing marine habitat to fishing may benefit fisheries significantly in the long run by enabling higher future catches outside the boundaries of the closed areas as stocks rebuild. Estimating these benefits, not to mention the value of protected species saved by reservation of habitat, lies outside the scope of the paper. We address only the short-term cost to the fishery of foregone harvesting opportunities, which is the cost that often poses the main political obstacle to creating such protected areas.

[3] For example, Smith and Wilen [29] studied the effects of creating MPAs for sea urchin in California. They used harvest location data from logbooks to partition the Northern California coast into eleven zones, separated by longitude.

[4] Guimares et al. [7] pioneered the use of probabilistic models of count data to approximate the RUM to model location decisions for industrial facilities among a large set of geographic choices.

[5] Mistiaen and Strand [17] developed and tested a short-run model of location choice for commercial fishers with heterogeneous risk preferences seeking to maximize their expected utility. They concluded that much is yet to be learned about estimating heterogeneous risk preferences among fishers and the policy implications stemming thereof.

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[6] For example, modeled and remote-sensed sea surface height are positively correlated, but the correlation coefficient is only 0.3, so we included both indicators for the 3km Gulf of Alaska analyses.

[7] Cloudiness disrupts satellite measurements of sea surface temperature (infrared) and chlorophyll (color in visible imagery). Satellite measurements of sea surface height tend to yield inaccurate readings near shallow coastlines affected by tidal action. Interference with land causes wind data to be unavailable in coastal areas where significant fishing takes place. Clouds and low light conditions combine to yield few if any valid chlorophyll readings in winter, and presence of sea ice also affects all winter satellite measurements.

[8] Remote-sensing data are generally provided as monthly climatologies at 7-10 km resolutions. After selecting a minimum usable quality level based on quality flags available with the data, we interpolated spatially to a common 3 x 3 km grid. We also interpolated as needed to map 12 monthly climatologies onto 26 potentially overlapping 2-week intervals.

[9] Since bathymetry is measured in meters, and horizontal distances in kilometers, we divided the formula result by 1000 to obtain bottom slope in degrees.

[10] All survey data points lie west of Middleton Island in the Central Gulf. The survey was taken in late spring and early summer -- starting in mid May and ending in mid July -- starting in west and moving east. Trawl gear used for the survey was limited to depths less than 600 meters. Despite these limitations, the NMFS survey data provides a spatially random sample taken with standard gear over a large geographic area.

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[11] Nearly all the 106 excluded sample points lie in the west end of the GOA (western portion of NMFS regulatory area 610).

[12] The 2001 Gulf of Alaska trawl survey was conducted from May 20 through July 23. Oceanographic model outputs are available for 14-day periods. The Julian days representing the start of each model period are 137, 151, 165, 179, and 193. Observer data include catch weights estimated from sampling portions of each observed haul. However, we do not use these data for estimating predicted CPUE. observed harvest locations may represent a spatially biased sample of fish density, since the fishing fleet is preferentially targeting (or may be avoiding in the case of unwanted bycatch) areas of the ocean where concentrations of fish are more likely to be found. Standard methods for addressing non-random sample selection may be able to correct for most of the bias, but the NMFS trawl survey provides an independent data set on fish density that obviates the need for such a procedure.

[13] Trawl vessels landed nearly all their catch at eight Alaska ports in 2001: Dutch Harbor, Akutan, King Cove, Sand Point, Kodiak, Kenai, and Cordova.

[14] For a nested model, the probability of selecting a grid cell would be a function of that cell's CPUE and an "inclusive value," representing the value of the set of future opportunities from the series of consecutive future hauls. The inclusive value at each level would depend on the value of the unknown parameter for the inclusive value at a lower choice level (corresponding to the next haul).

[15] The spatial sampling is stratified to improve accuracy of total biomass estimates [21]. Since our interest is in understanding spatial variation fish density rather than total area-wide biomass, we ignore the strata weights in our analysis.

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[16] One could in theory also project the CPUE equations forward into the early spring and winter months. However, behavioral changes in groundfish associated with spawning during the winter fishery casts doubt on the usefulness of such an out-of-season prediction.

[17] The variance multiplier for pollock had to be approximated by estimating the equation with a fixed value for the scale factor, changing the value until the log likelihood stopped increasing.

[18] We excluded grid cells from the choice set that were subject to regulatory closures during the entire model period. For pollock, some hauls occurred in areas that were open for a portion of the period. For Pacific cod, hardly any hauls were observed in such "partially closed" areas, so no coefficients could be estimated.

[19] These were Seguam Pass, Bogoslof, and Shelikof Strait. See Designated Critical Habitat; Steller Sea Lion, 58 Fed. Reg. 45,269 (Sept. 27, 1993) (50 C.F.R. pt. 226). McBeath [15] discussed the litigation history and policy issues related to the SSL case.

[20] According to NMFS, "The portion of the catch sampled by observers varies by region, vessel-type, gear-type, and target fishery. Since 2001, vessels with observers in the BSAI have accounted for approximately 90% of the groundfish tonnage caught and observers have sampled the catch from about three-fourths of the hauls/sets. Vessels with observers in the GOA have accounted for approximately 40% of the groundfish tonnage caught and observers have sampled the catch from about two-thirds of the hauls/sets." (http://www.afsc.noaa.gov/FMA/spatial_data.htm) The estimates in Table 4 suggest that the mixed trawl offshore fishery is more profitable than any of the onshore fisheries. However, one should be cautious in interpreting the result, given that the mixed trawl

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fishery includes values for sablefish bycatch, for which reliable ex vessel price data do not exist.

[21] The empirical results for the different statistical analyses do provide some insights into the likely nature and magnitude of the uncertainty in the estimates. First, the total values and values per haul are inversely proportional to the magnitude of the coefficient on CPUE in the negative binomial regressions. Confidence intervals around this coefficient are quite precise (t statistics around 3) for all fisheries. Since the coefficient on CPUE scales total values estimated both with and without the habitat regulations, the estimated values as expressed in Table 5 in percentages of potential profits are relatively insensitive to the magnitude of the CPUE coefficient.

Figure 1. Location of NMFS 2001 Gulf of Alaska trawl survey hauls (orange) and observed trawl fishery hauls (green).

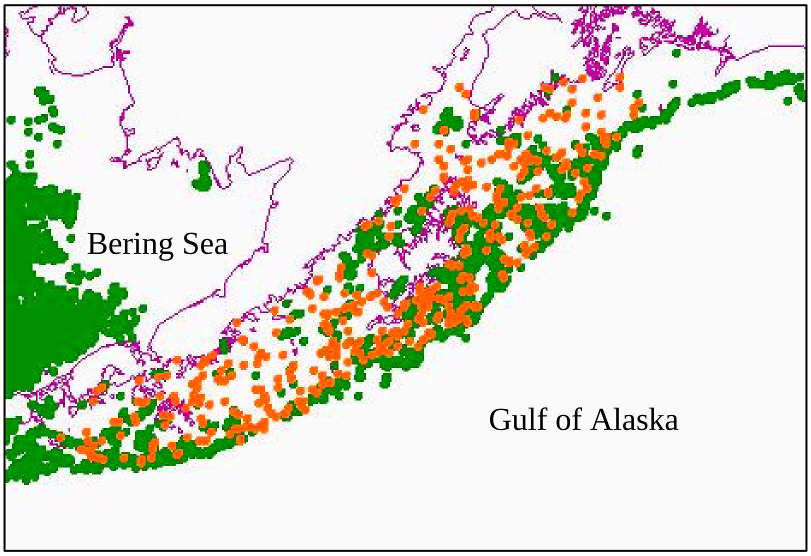

Figure 2. Estimated spatial values of shore-based Pacific cod fisheries in the Gulf of Alaska, summer-fall 2001, and boundaries of Steller sea lion closed areas. (Darker color indicates higher value; Chiniak Gulley research closure outlined in red.)

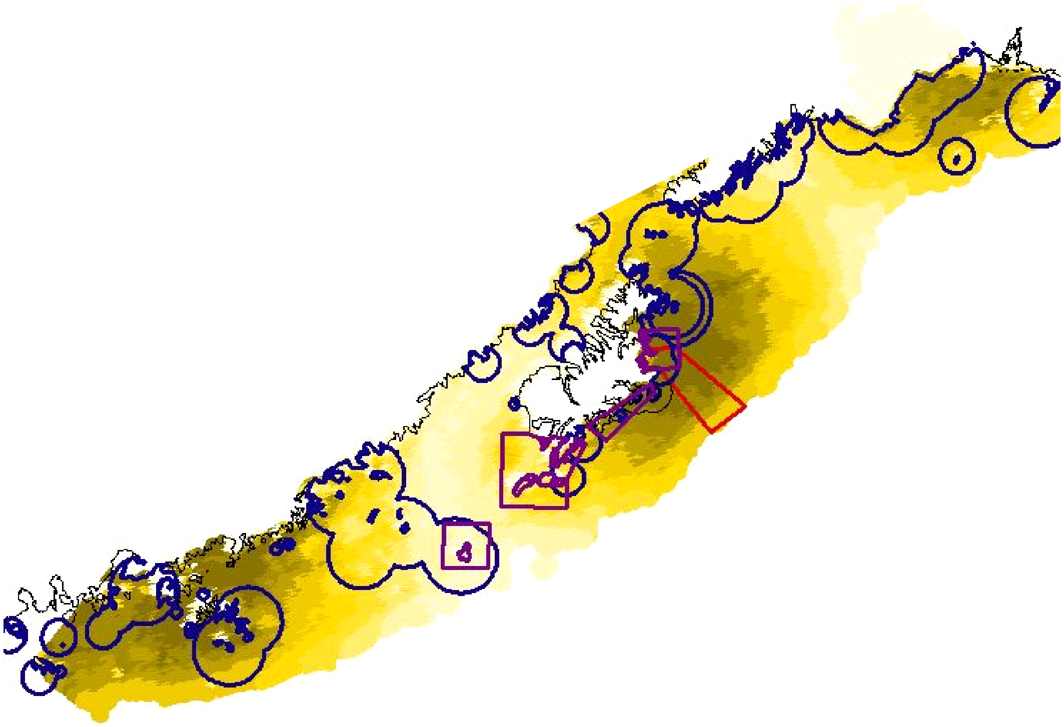

Table 1. Environmental Variables Predicting Catch per Unit of Effort

Variable	*Definition*	*Source*
ldepth	natural logarithm of bottom depth, in metres	trawl survey
l2dep	square of nat. log of bottom depth	calculated
timeldep	julian day times ldepth	trawl survey, calc.
lslope	natural logarithm of slope at 3km resolution	NOAA, calculated
l2slope	square of nat. log of slope	calculated
lmld	natural logarithm of mixed layer depth, in metres	ROMS model
lmld_dep	nat. log. of mixed layer depth times nat. log. of bottom depth	calculated
lstem	natural logarithm of surface temperature	trawl survey
lgtem	natural logarithm of gear temperature at fishing depth	trawl survey
l2gtem	square of natural logarithm of gear temperature	calculated
lmtem	natural logarithm of temperature below mixed layer depth	ROMS model
lmstem	nat. log of temperature at depth minus nat. log of surface temp	ROMS model
lbmtem	nat. log of bottom temperature minus nat. log of temp at depth	ROMS model
lmsal	natural logarithm of salinity below mixed layer depth	ROMS model
lmssal	nat. log of salinity at depth minus nat. log of surface salinity	ROMS model
lbmsal	nat. log of bottom salinity minus nat. log of salinity at depth	ROMS model
vervelbm	vertical velocity at level below mixed layer depth (10^{-3}m/s)	ROMS model
msvervel	vertical velocity at depth minus vertical vel. at surface (cm/s)	ROMS model
bmvervel	vertical velocity on bottom minus vertical vel. at depth (cm/s)	ROMS model
horvelbm	horizontal velocity at level below mixed layer depth (cm/s)	ROMS model
mshorvel	horizontal velocity at depth minus hor. vel. at surface (cm/s)	ROMS model
bmhorvel	horizontal velocity on bottom minus hor. vel. at depth (cm/s)	ROMS model
ssh	modeled sea surface height, in metres	ROMS model
sshrs	average monthly sea surface height, in metres x 10^{-2}	Remote-sensed
lchla	natural logarithm of chlorophyll, current period	Remote-sensed
lchla1	natural logarithm of chlorophyll, one-period (14-day) lag	Remote-sensed
lchla2	natural logarithm of chlorophyll, two-period (28-day) lag	Remote-sensed
lwind	natural logarithm of average wind speed	Remote-sensed

Table 2. Censored Regressions for Groundfish Catch per Unit of Effort, NMFS Gulf of Alaska Trawl Survey, Summer 2001

Maximum Likelihood Estimates
(t statistics in parentheses)

Dependent variable: natural logarithm of fish weights in kg. per trawl minute

Dep. Var.	*Pacific cod, average weight > 0.5 kg*		*Pollock, average weight > 0.25 kg*		*Black cod, average weight > 0.75 kg*		*Flatfish, average weight > 0.5 kg*		*Rockfish, average weight > 0.5 kg*	
Constant	1189.3		-4805.1	***	-466.94	***	3835.4	**	-410.09	***
	1.067		-2.672		-5.191		1.966		-4.75	
J162	3.5561	***	3.1049	***	4.1629	***	3.0538	**	-1.9281	
	2.713		2.643		2.759		2.202		-1.105	
J177	4.8798	**	3.4288	***	7.3562	***	4.309	*	-1.3962	
	2.338		2.628		2.909		1.885		-0.575	
J192	5.9164	**	4.6284	**	8.7336	**	6.6923	**	-7.0661	*
	2.003		2.399		2.613		2.163		-1.931	
LDEPTH	32.248	***	12.433	***	7.1558	***	-21.097	***		
	4.112		5.961		7.22		-2.947			
L2DEP	-2.898	***					2.597	***		
	-3.561						3.48			
TIMELDEP									0.03797	***
									3.689	
LSTEM	-4.0984	**							-6.2988	*
	-2.061								-1.93	
LGTEM	218.32	***	127.18	***	115.82	***	125.55	***	171.57	***
	5.181		4.171		3.546		4.33		3.487	
L2GTEM	-56.37	***	-33.342	***	-31.303	***	-32.519	***	-47.574	***
	-5.028		-4.009		-3.344		-4.246		-3.491	
LSLOPE	1.4928				0.31719		0.98501	***		
	1.453				1.374		3.575			
L2SLOPE	-0.20927								-0.08787	
	-1.119								-1.218	
LMLD			12.36	***			-2.5635	**	8.5802	*
			2.853				-2.308		1.798	
LMLD_DEP			-2.1187	**					-2.141	**
			-2.339						-2.121	
LMTEM	-9.4971	*			-10.21	*	-7.6277			
	-1.898				-1.75		-1.378			
LMSTEM	15.221	*			13.796		30.724	***		
	1.82				1.568		3.034			
LMSAL	-805.2		2799.5	***	97.421	***	-2244.3	**	69.276	***
	-1.235		2.676		3.334		-1.973		2.929	
L2MSAL	110.77		-423.15	***			323.27	*		
	1.163		-2.775				1.952			
LMSSAL					34.048	**	-42.533	*		
					2.18		-1.941			
LBMSAL	-62.086	***	-82.426	***	70.359	**	-41.613	**	58.733	*
	-3.689		-4.35		2.266		-2.269		1.961	
VERVELBM									-33.644	**
									-2.068	
HORVELBM	0.13319		-0.03519		-0.17467	**	-0.19004	*		

	1.45		-1.35		-2.178		-1.874			
MSHORVEL	-0.16556	*			0.13521	*	0.17784	*	-0.06387	
	-1.705				1.692		1.674		-1.57	
BMHORVEL									0.30568	*
									1.703	
SSHRS					0.17729					
					1.455					
LCHLA	0.47038		2.7487	***						
	1.047		3.86							
LCHLA1			-1.6501	**	2.1955	**	1.0526	**		
			-2.243		2.482		1.976			
LCHLA2					-1.1974					
					-1.425					
Sigma	3.4294	***	3.5479	***	2.4939	***	4.0471	***	5.0184	***
	16.455		13.551		15.633		19.798		13.334	
Mean of LHS	1.75		1.13		1.70		3.83		1.34	
Observations	381		380		374		380		391	
Restr.Log-L	-833.45		-793.65		-849.62		-973.1		-894.93	
Log-likelihood	-570.8	***	-421.77	***	-391.25	***	-794.34	***	-471.12	***
χ squared	525.3		743.8		916.7		357.4		847.6	

*$p < 0.1$
** $p < 0.05$
***$p < 0.01$

Table 3. Negative Binomial Regressions for Distribution of Summer and Fall 2001 Gulf of Alaska Groundfish Trawl Fishing Effort

Maximum Likelihood Estimates
(t statistics in parentheses)

Dependent variable: number of target fishery hauls observed
(Biweekly fixed effects not shown)

	pollock trawl		*Pacific cod trawl*		*other trawl onshore*[a]		*other trawl offshore*	
Expected CPUE, pollock	0.0007414	***			-0.01313	**		
	(3.02)				(-2.07)			
Expected CPUE, Pacific cod			0.07873	***				
			(3.49)					
Expected CPUE, rockfish					0.09464	*	0.02694	***
					(1.73)		(3.06)	
Expected CPUE, flatfish					0.03951	**		
					(2.15)			
Expected CPUE, black cod					0.02056	*	2.082E-04	*
					(1.69)		(1.83)	
Expected neighborhood CPUE, rockfish							0.06038	**
							(2.94)	
Distance to port (km)	-0.01665	***	-0.01223	***	-0.01282	***		
	(-14.36)		(-7.46)		(-5.40)			
Fishery regulatory opening	5.5433	***						
	(3.91)							
Fishery SSL habitat closure	-1.4517	***						
	(-5.39)							
Variance Scale	100		136.28	***	50		150	
	--		(6.42)		--		--	
Log-likelihood	-898.5		-875.1		-308.0		-946.5	
Initial Log-Likelihood	-1350.9		-1312.6		-2840.0		-1246.0	
Likelihood ratio χ squared	904.7	***	875.0	***	5,064	***	599.7	***
Observations	105,205		93,219		22,403		42,435	

[a] Estimated based on a random 10 percent sample of unfished grid cells.

*$p < 0.1$
** $p < 0.05$
***$p < 0.01$

Table 4. Estimated Net Value of Summer and Fall 2001 Gulf of Alaska Groundfish Trawl Fisheries, and Opportunity Cost of Critical Habitat Closures

	Pollock	*Pacific cod*	*Other shore-based*[c]	*Rockfish offshore*
Fishery open time periods	19-23	19-23	12-23	15-16
Mean fishing area per period (000 km^2)	181.6	174.3	188.7	213.0
Observed hauls	205	184	546	205
Mean value per km^2	$0.74	$1.13	$2.05	$3.08
Std Dev. ov mean value	1.41	2.39	5.38	3.18
Mean value per haul	$3,274	$5,351	$8,498	$6,394
Implied total value ($000s)[a]	$2,514	$3,688	$17,378	$4,909
Value in closed Critical Habitat ($000s)[a, b]	$701	$1,227	$33.9	$8.65
Percentage of total value in closed Critical Habitat	27.9%	33.3%	0.20%	0.18%

[a] Assumes 26.7 percent of hauls observed.

[b] Chiniak Gulley research trawl area is not included in closed Critical Habitat.

[c] Estimates based on a random 10 percent sample of unfished area.

Table 5. Estimated Opportunity Cost for the Gulf of Alaska Groundfish Trawl Fisheries of the 2001 Chiniak Gulley Research Trawl Closure

	Pollock	*Pacific cod*	*Other shore-based*[b]	*Rockfish offshore*
Fishery time periods during research closure	19	19	17-19	none
Mean open fishing area during research closure (000 km^2)	193.8	218.9	152.4	-
Observed hauls	80	49	118	-
Mean value per haul in closed area	$84	$193	$134	-
Implied total value of closed area ($000s)[a]	$25.2	$35.4	$59.2	-
Percentage of total value in closed Chiniak research area	1.0%	1.0%	0.34%	0.00%

[a] Assumes 26.7 percent of hauls observed.

[b] Estimates based on a random 10 percent sample of unfished area.