Spatial Patterns of Renewable Resource Exploitation:
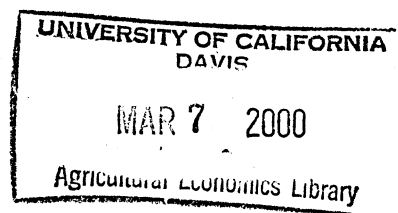## The California Sea Urchin Fishery

by

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Abstract: This paper analyzes spatial patterns of exploitation in the California sea urchin fishery. A Random Utility Model of urchin diver participation and location choice yields a conditional logit specification. Results demonstrate that diver attributes, location-specific features, and characteristics of individual days are important determinants of harvester choices.

Spatial Behavior of Renewable Resource Harvesters:
The California Sea Urchin Fishery[*]

Most models of renewable resource exploitation treat the resource as homogeneous and uniformly spread over space. Recent developments in ecology, however, highlight the manner in which patchiness and heterogeneity of prey and food sources affect the spatial distribution of populations. Drawing on these developments, biologists and fisheries managers have proposed spatial policy options, including (permanent) marine reserves and (temporary) rotating harvest zones, as the primary means to preserve certain marine fisheries. In order to contribute to the policy debate surrounding these measures, economists must focus attention on the spatial character of resource exploitation.

The sea urchin fishery is an ideal case for studying spatial decision making. Divers harvest urchins in areas off the coast down to 100 feet in depth. They take mostly day trips in order to ensure the freshest quality of the roe, which is marketed as a traditional delicacy in Japan. The most important daily decisions concern dive locations; divers search for patches of urchin in high abundance and of high quality (recovery rate and roe quality).

The short-run policy relevance of this work is to address the sustained viability of California's sea urchin fishery. Until recently, the demand for high quality sea urchin roe was met primarily by harvests of Japanese urchin. Though a different species than the Japanese urchin, California's red sea urchin, *Strongylocentrotus franciscanus*, yields a product with similar taste and quality. As a result of this substitutability and concerns over devastation of giant kelp forests (due in part to urchin foraging), a commercial sea urchin fishery developed in Southern California in the late 1970's and began exporting to Japan. By the late 1980's

commercial urchin diving had expanded to Northern California. In response to declining

Japanese urchin harvests, the sea urchin fishery in California has grown to become the state's

second most valuable fishery. However, catch rates have declined since the early 1990's, with a

dramatic decline in Northern California. These declines have worried regulators and have

initiated a debate about spatial management options in the sea urchin fishery.

This research has several important implications in addition to answering the immediate

policy question. First, little is known about how renewable resource harvesters actually

incorporate spatial heterogeneity of resource abundance into decision making. This paper

explores the nature of the decision process. Second, creation of permanent marine reserves is a

management option being considered in many fisheries throughout the world, but little is known

about how they will displace harvesters or how they will affect long-term resource productivity.

This paper develops and estimates a spatial behavior model of renewable resource

harvesters in the sea urchin fishery off California. To study diver participation and location

choices we propose a random utility model. The resulting conditional logit analysis

demonstrates that diver attributes, location-specific features, and characteristics of individual

days are all important determinants of harvester choices. The immediate goal is to understand

the behavioral motivations underlying spatial location choices among these resource users. The

long-term goal is to use this understanding to predict the impacts of various spatially-explicit

policy options with a particular focus on how fishermen will adjust when they are excluded from

areas they have traditionally fished.

Literature Review

The essential fisheries work begins with Gordon (1954) and V. Smith (1968). They show

how an open access institutional setting leads to a rent dissipation process in which

overexploitation of a fishery can occur. Sanchirico (1998) and Sanchirico and Wilen (1999a) apply this framework to a spatially heterogeneous resource and reach similar conclusions about rent dissipation. In their case, rents appear as spatial arbitrage opportunities that arise due to the spatial character of biological dynamics. An open access equilibrium occurs when all spatially-explicit rents are driven to zero. These studies all highlight the need for regulation of a commercial fishery.

Three recent papers have addressed the particular issue of permanent marine reserves from a bioeconomic perspective. Holland and Brazee (1996) analyze conditions under which marine reserves are likely to succeed as a regulatory policy. Though the authors provide an interesting discussion of biological and economic issues, the results of the analysis are driven by an assumption that total fishery effort is fixed. Moreover, the model only incorporates spatial heterogeneity as a difference between reserve and non-reserve areas. Hannesson (1998) also analyzes marine reserves and compares pure open access and private ownership institutional settings. Rents are generated by the marine reserve as fish disperse outside the reserve. But, when there is open access outside the reserve, these rents are dissipated as in the standard case. Sanchirico and Wilen (1999b) incorporate more biological sophistication in their study of marine reserves and suggest specific biological characteristics that would likely lead to successful implementation of marine reserves. Specifically, when patches are biologically linked (i.e. there is dispersal between patches), it is possible that reserve creation under open access can both increase aggregate harvests and aggregate biomass. While the existing papers on marine reserves highlight some of the key issues, they are all theoretical and do not address the institutional details of any particular policy setting. Moreover, several empirical fisheries studies have analyzed spatial behavior of harvesters, e.g. Hilborn and Ledbetter (1979, 1985), Hilborn

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(1985), Abrahams and Healey (1990), and Evans (1997), but our paper begins the first econometric study of the potential for marine reserves.

In addition to the economic literature, several articles provide useful information about urchin biological and oceanographic factors that relate to marine reserves and background on the development of the urchin fishery in California. These include Kato and Schroeter (1985); Botsford, Quinn, Wing, and Brittacher (1993); Quinn, Wing, and Botsford (1993); and Kalvass and Hendrix (1997). Finally, the Sea Urchin Harvester Association of California newsletter, *Light and Variable,* provides further industry information.

Empirical Model

Urchin divers make a series of discrete and continuous decisions about fishing effort and location. Figure 1 depicts the first part of a diver's decision tree for one season. The diver chooses a home port at the beginning of a season, which ultimately limits the choice set of fishing locations due to travel times. Then on each open season day, each diver chooses whether or not to participate based on prevailing weather conditions, expected prices, expected resource abundance, individual diver traits, and processor contractual arrangements with the Tokyo wholesale market. Among the individual traits are diver skill, attitudes towards risk, outside opportunities, and values of leisure time. Divers who have chosen to participate then choose diving locations based on expectations about spatially varying resource abundance, travel costs, and weather conditions. Finally, they choose diving hours, a continuous variable, once they observe local weather and resource abundance. The sequence of daily decisions repeats for each day in the season without structural change, but available information changes as conditions change over time and as divers learn more about the spatial distribution of urchin abundance.

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As a first step in analyzing urchin diver spatial behavior, we posit a Random Utility Model to study discrete daily participation decisions and diving location decisions. Index individuals by i, diving locations by j, and days by t. Diver i's utility from diving in harvest zone j on day t is:

$$U_{ijt} = v_{ijt} + \varepsilon_{ijt}$$
$$= \mathbf{X_{it}}'\beta + \mathbf{Z_{ijt}}'\gamma + \varepsilon_{ijt}$$

where $\mathbf{X}$ includes diver-specific and time-specific characteristics that are constant across choices and $\mathbf{Z}$ denotes choice-specific characteristics. We express the utility of not diving at all on a given day as:

$$U_{inot} = \alpha + \varepsilon_{inot}$$

where α is a constant that captures both the value of leisure and work opportunities outside the urchin fishery. Given M possible diving locations, the Random Utility Model posits that a diver chooses location 1 if the utility of choice 1 is higher than that of the (M-1) other location choices as well as the choice of not to dive. For example:

$$\Pr[i \text{ chooses } 1 \text{ at } t] = \Pr[U_{i1t} > U_{i2t}, U_{i1t} > U_{i3t}, ..., U_{i1t} > U_{iMt}, U_{i1t} > U_{inott}]$$

Assuming that the ε's are indepedently and identically distributed Type I Extreme Value, utility maximization gives rise to the familiar Conditional Logit Model (McFadden, 1974). The choice probabilities are thus as follows:

$$p_{i\,not\,t} = \frac{e^{\alpha}}{e^{\alpha} + \sum_{j=1}^{M} e^{X_{it}\beta + Z_{ijt}\gamma}}$$

$$p_{i1t} = \frac{e^{X_{i1t}\beta + Z_{i1t}\gamma}}{e^{\alpha} + \sum_{j=1}^{M} e^{X_{it}\beta + Z_{ijt}\gamma}}$$

$$\vdots$$

$$p_{iMt} = \frac{e^{X_{iMt}\beta + Z_{iMt}\gamma}}{e^{\alpha} + \sum_{j=1}^{M} e^{X_{it}\beta + Z_{ijt}\gamma}}$$

Data

The fishery data, collected by the California Department of Fish and Game, include 257,000 observations on California urchin dives over the period 1988-1997. Each observation combines geographically-specific log book information about dive duration, depth, number of divers, and pounds caught with landings ticket information about price, quantity sold, landing site, and diver license. We divided Northern California into eleven geographically distinct harvest zones that roughly correspond to proposed spatial management zones. Figure 2 shows the spatial distribution of effort in north-central California. The northern-most zone does not appear in Figure 2 because it is at a higher latitude. The Farallon Islands zone also does not appear because it is off further off the coast, but it is located approximately at the break between patches 1 and 2. Though there are six total ports in Northern California at which divers land urchin, the four ports depicted in Figure 2 account for more than 90% of Northern California catch. Table 1 shows how individual divers exhibit different levels of mobility; some divers fish in many locations while others fish in very few locations. We also have collected geographically specific weather data from the National Buoy Data Center. These data contain hourly observations on variables that affect diving conditions including wave height, wave period, and

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wind speed. We aggregated these data into daily observations and linked them to the urchin databases.

For empirical analysis, **X** includes price (PRICE), wave period (WP), wind speed (WS), wave height (WH), diver tenure (TENURE), diver past catch per unit effort (DCPUE), diver cumulative number of dives (CUMDIV), number of divers on the boat (DIVERS), and day-of-week dummies (SUN, …, SAT). For each location, **Z** contains patch-specific catch per unit effort (a measure of urchin abundance in each location) (CPUE), travel distance from the diver's home port (DISTANCE), and a variable that interacts DISTANCE with DIVERS (DIS*DIV). As a consequence of the day-of-week dummies, we cannot identify a separate coefficient α and thus set it to 0, which ensures identification of all other model parameters. Daily decisions are made on each open-season day, of which there are approximately 200 per year. To construct the subset of data used for analysis, we randomly selected thirty divers, followed them over the entire sample period of ten years, and truncated daily decisions before a diver's first dive and after the diver's last dive.

Results and Conclusions

Table 2 reports results from conditional logit analysis on the 27,822 observations. All coefficients are statistically significant at the 5% level except the coefficient on divers per boat (DIVERS) and several of the day-of-week dummies. The positive sign on PRICE suggests that divers are more likely to dive when prices are high. The negative coefficients on weather variables (WP, WS, and WV) all indicate that the probability of diving decreases when weather conditions are unfavorable. Wave period and height measure wave power, which increases the safety risk of diving, and wind speed is a general indicator of harsh weather.

The signs on TENURE, DCPUE, and CUMDIV have less obvious interpretations. One possible explanation for the sign on TENURE is that more experienced divers only participate when conditions are good (e.g. urchin roe content is high due to spawning cycles). An alternative explanation is that TENURE picks up an age effect; more experienced divers are older and cannot participate as often in physically strenuous activities like urchin diving. An explanation for the negative sign on DCPUE is based on the idea that individual diver catch per unit effort measures diver skill. In contrast to CPUE, DCPUE is not a measure of urchin abundance. It is also worth noting that the magnitude of the CPUE coefficient is much greater than that of DCPUE. Similar to the first interpretation of TENURE, highly skilled divers may be more professionalized and participate only when diving conditions are good. CUMDIV appears to indicate an individual diver's propensity to dive. Divers who have gone many times in the past are more likely to go again. More interestingly, this variable may partially reflect diver outside opportunities. Frequent divers may have lower outside employment opportunities, may attach a lower value to leisure throughout the sample period, or may be less risk averse towards unsafe diving conditions.

The day-of-week dummies demonstrate the importance of urchin roe market institutions. It is important to note that lack of statistical significance for some dummies is unimportant; the pattern of the effects is what is relevant as well as their being signficantly different from each other.[1] Most California urchin roe processors are closed on Sundays, so there is less diving activity on weekends. Urchin landings on late Thursday or early Friday may be shipped to Japan Friday night and arrive in Japan Sunday. Since the Tokyo wholesale market is closed on

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[1] Since the pattern includes both positive and negative coefficients, it is no surprise that some are not statistically different from zero. In a previous run that set $\alpha=1.5956$ rather than $\alpha=0$ (essentially a re-scaling), all day-of-week dummies were statistically significant at the 5% level.

Sundays, this decreases fishing effort at the end of each week. Thus, diver participation is greatest in mid-week.

Patch-specific variables are also important explanatory variables. The sign of CPUE is positive and indicates that divers do indeed seek patches with high urchin abundance. The negative sign on DISTANCE suggests that travel costs deter divers from venturing far from their ports. Finally, the positive sign on DIS*DIV has an interesting spatial economies of scale interpretation. It suggests that when there are multiple divers on a boat, the fixed costs of travel are spread over multiple individuals, which partly offsets the DISTANCE variable.[2]

Future Work

The first step in the future is to extend the empirical decision analysis to include the fully nested structure of port choice, participation, and diving location choice. This will allow us to simulate spatial closures, since undoubtedly some divers will change ports as a result of spatial management. In this setting, conditional logit becomes problematic because it imposes Independence of Irrelevant Alternatives (IIA), which would severely limit the scope of policy analysis. IIA would impose the assumption that effort from a closed patch redistributes among remaining patches such that relative choice probabilities remain the same. Possible future directions inlcude nested logit and multinomial probit. Multinomial probit explicitly allows for correlation among unobserved attributes of geographically contiguous fishing locations, and recent developments in simulation-based estimation have made multinomial probit models more feasible to estimate.

Since the exploratory data analysis has shown considerable variation in mobility, performance, and participation rate across individuals, an explicit model of diver heterogeneity is

essential for future analysis. This raises two challenges: 1) most individual characteristics are unobservable and must be modeled accordingly, and 2) one must distinguish between state dependence and heterogeneity. A method to obtain consistent estimates and account for unobserved diver heterogeneity is use of random coefficients within the probit or logit index functions. We can incorporate unobserved location heterogeneity in a similar fashion. Assuming a linear index function, random utility can be expressed as:

$$U_{ijt} = \mathbf{X_{it}}'\beta + \mathbf{Z_{ijt}}'\gamma + \varepsilon_{ijt}$$
$$= \mathbf{X_{it}}'(\bar{\beta} + \eta_i) + \mathbf{Z_{ijt}}'(\bar{\gamma} + \delta_j) + \varepsilon_{ijt}$$
$$where\, \eta_i \sim N(0, \Sigma_\eta)\, and\, \delta_j \sim N(0, \Sigma_\delta)$$

Again, random parameters discrete choice models have been made possible by the developments in simulation-based estimation. Thus, simulation-based estimation is potentially required for two aspects of the problem: integrating over random parameters within the index functions and approximating integrals of multivariate normals from the probits. How to account for state dependence in a multinomial setting is less clear. Several examples from consumer product choice provide guidance for dealing with state dependence and heterogeneity, but the state dependence specifications are generally *ad hoc*.[3]

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[2] A different justification, however, can be made for the interactive variable having the opposite sign. Divers on multi-diver boats drive to a different port to reduce travel costs, since we expect that travel by boat is more costly and time-consuming than travel by car.

[3] See, for example, Keane (1997), Guadagni and Little (1983), Erdem and Keane (1996), and Allenby and Rossi (1999).
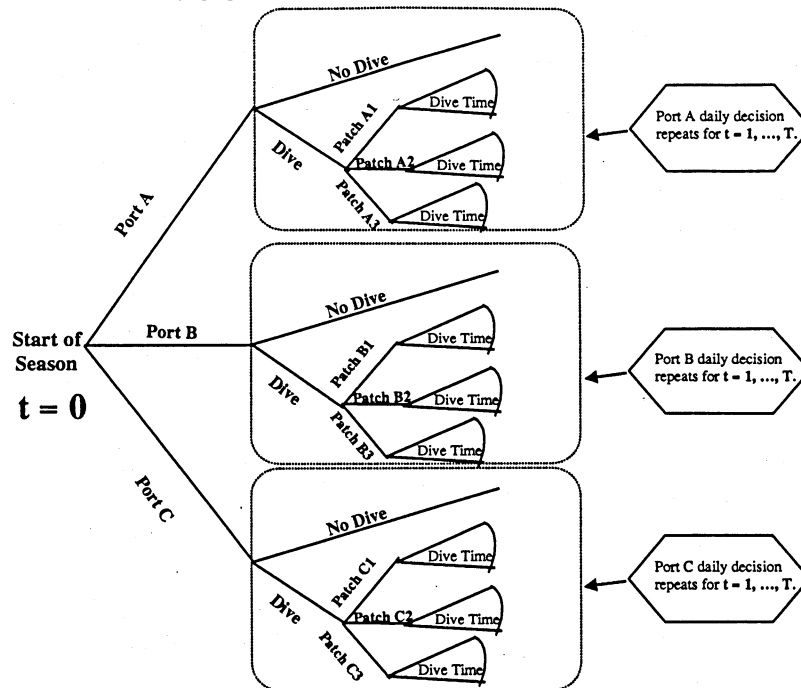
Figure 1
Urchin Diver Decision Tree

Port A daily decision repeats for t = 1, ..., T.

Port B daily decision repeats for t = 1, ..., T.

Port C daily decision repeats for t = 1, ..., T.

Figure 2
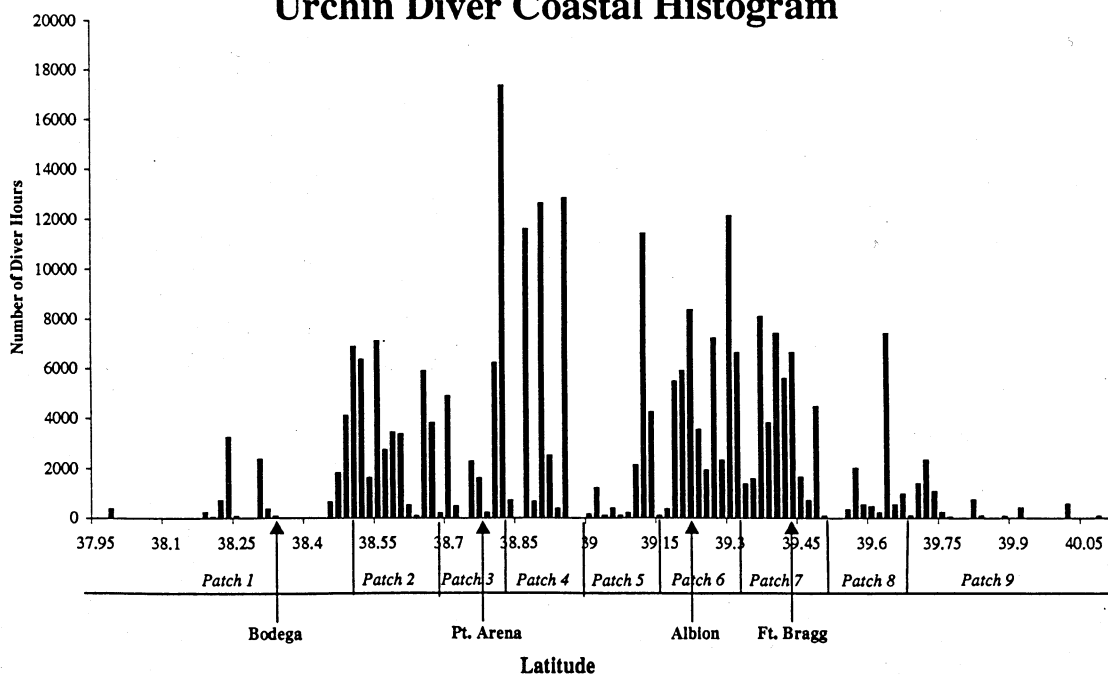# Urchin Diver Coastal Histogram

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Table 1: Diver Spatial Activity

Number of Patches Active In	1988 Number of Divers	1989 Number of Divers	1990 Number of Divers	1991 Number of Divers	1992 Number of Divers	1993 Number of Divers	1994 Number of Divers	1995 Number of Divers	1996 Number of Divers	1997 Number of Divers
1	19	27	41	32	36	32	19	24	20	19
2	31	52	73	75	59	59	69	49	50	40
3	24	17	60	59	45	42	34	24	23	21
4	10	8	33	36	32	34	33	24	18	12
5	3	2	22	15	37	18	13	17	5	5
6	3	0	11	14	22	15	6	4	3	2
7	0	0	4	11	16	12	11	3	0	0
8	0	0	1	8	6	5	3	1	1	0
9	0	0	1	2	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0
Total Divers	90	106	246	252	253	217	188	146	120	99
Weighted Average	2.51	2.11	2.93	3.26	3.53	3.30	3.15	2.93	2.60	2.49

Table 2: Conditional Logit Results

	Coefficient	Estimate	Standard Error	Z Statistic	P-Value
β_1	PRICE	0.304	0.082	3.716	0.000
β_2	WP	-0.148	0.023	-6.346	0.000
β_3	WS	-0.076	0.013	-5.881	0.000
β_4	WH	-0.777	0.047	-16.666	0.000
β_5	TENURE	-0.488	0.023	-21.090	0.000
β_6	DCPUE	-0.034	0.014	-2.433	0.008
β_7	CUMDIV	0.150	0.005	32.889	0.000
β_8	DIVERS	0.033	0.047	0.688	0.246
β_9	SUN	-0.776	0.233	-3.332	0.000
β_{10}	MON	-0.083	0.217	-0.381	0.352
β_{11}	TUE	0.035	0.217	0.161	0.436
β_{12}	WED	-0.055	0.217	-0.253	0.400
β_{13}	THU	-0.155	0.220	-0.704	0.241
β_{14}	FRI	-0.636	0.230	-2.768	0.003
β_{15}	SAT	-0.695	0.229	-3.036	0.001
γ_1	CPUE	0.131	0.020	6.732	0.000
γ_2	DISTANCE	-6.160	0.369	-16.692	0.000
γ_3	DIS*DIV	0.346	0.176	1.971	0.024

Log-likelihood   -10479.4067

Observations   27822

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