Potential Economic Benefits and Optimum Fleet Size in the Pacific Coast Trawl Fleet

Daniel D. Huppert
Dale Squires

National Marine Fisheries Service
Southwest Fisheries Center
P.O. Box 271
La Jolla, California

Abstract Limiting entry to the Pacific coast groundfish fishery poses two principal questions: (1) How large are the potential economic returns under limited access management? and (2) Will the economic benefits exceed the program costs plus costs associated with transitory dislocations in the fishery? This paper reports on a partial evaluation of the first question, based on a mixed integer programming model that computes optimum fleet size, fishing effort configuration, and associated economic surplus. The multispecies fishery, economic parameters, annual harvest constraints, and summary results are presented. Overall, a maximum economic profit of about $12 million can be generated by a trawl fleet that is about 38 percent smaller than the baseline 1984 fleet with a 23 percent reduction in weeks fished. Another important conclusion is that economic profits would suffer if fishing vessels are prevented from shifting among groundfish, pink shrimp, and joint venture fisheries.

Marine Resource Economics, Volume 3, Number 4
0738–1360/87/030297–00$03.00 + 0

Introduction

The principal objective of this paper is to evaluate the magnitude of economic benefits from limiting access to the Pacific coast trawl fishery. An extensive literature describes the conceptual advantages and disadvantages of various approaches to limited access (Christy, 1973; Rettig and Ginter, 1978; Stokes, 1979; Young, 1983; Rettig, 1984). Ideally, a fishing industry under limited access will minimize the cost of catching the sustainable biological yield. This should create a source of surplus economic value which may be collected as rent by public agencies or retained as profit by private industry. As a practical matter, to justify a new limited access regime it needs to be shown that potential economic surplus exceeds the social and economic costs associated with temporary dislocations and continuing program administration. In anticipation of the need for evaluating limited access in Pacific groundfish we evaluate the optimum fleet size and fishing effort patterns for a profit-seeking centralized owner/manager of the fishery. This estimate provides a useful benchmark for program evaluation, and it represents the social opportunity cost of not adopting limited access.

The Pacific coast trawl fishery is represented by a linear production model, which assumes that several varieties of fishing effort are each supplied at fixed unit costs and that the catch for each variety of fishing effort is proportional to the level of effort. A mixed integer programming algorithm is used to compute the maximum economic surplus subject to constraints on the annual harvest of various groundfish species and constraints on the amounts of fishing effort that fishing vessels can exert. Fish prices, fixed and variable fishing costs, and catch rates for each species are determined from data on the fishery. The solution gives optimum numbers of vessels, optimum allocation of fishing effort, and maximum economic value.

Several recent studies have applied linear programming (LP) to multispecies fisheries. Brown et al. (1979), Siegel et al. (1979), and Overholtz (1985) develop LP models of the New England trawl fishery. Each of these uses a harvest production model in which fishing is directed toward target species while "bycatch" of other species is taken in smaller quantities. Although the term "bycatch" may be a useful descriptive device in some fisheries, we find that trawl vessel captains frequently harvest two or more species in combination without considering one species to be a bycatch (i.e., a coincidental or unplanned consequence) of another target species. Without identifying any species to be a target or a bycatch, the Pacific trawl model specifies a joint production technology consisting of several fixed-proportions multispecies fishing modes. The mix of species caught per unit effort varies among vessel sizes, among seasons, and among fishing modes. In contrast to the New England models this model adopts maximum economic surplus, rather than maximum catch or maximum exvessel value of catch, as the objective.

The Pacific Coast Trawl Fishery

Both the trawl fleet and the fish stocks are spread among three major areas of the Exclusive Economic Zone off the Pacific coast (Figure 1). The northernmost area consists of the International North Pacific Fisheries Commission's (INPFC) Columbia area and a portion of the Vancouver area. The middle area is INPFC's Eureka area, which includes the major southern Oregon and northern California ports. The southernmost area, Monterey, covers central California. We have not included the INPFC Conception area because little groundfish trawling occurs there.

A total of fifty-one species are considered in the trawl fleet model. Forty-nine groundfish species are grouped into eight major categories (Table 1). Dover sole, sablefish, widow rockfish, and Pacific whiting are each treated separately due to their importance to the fishery, availability of specific stock assessments, and consistency with management regulations. Eight species are grouped in "other flatfish," the most important of which are English and petrale sole, flounders, and sand dabs. "Other rockfish" includes twenty-four *Sebastes* and *Sebastolobus* species. Pacific cod and ling cod are placed in a separate group, because they are distinct from the flatfish and rockfish species in both biological and economic characteristics. The miscellaneous group includes various sharks, skates, rays, grenadiers,

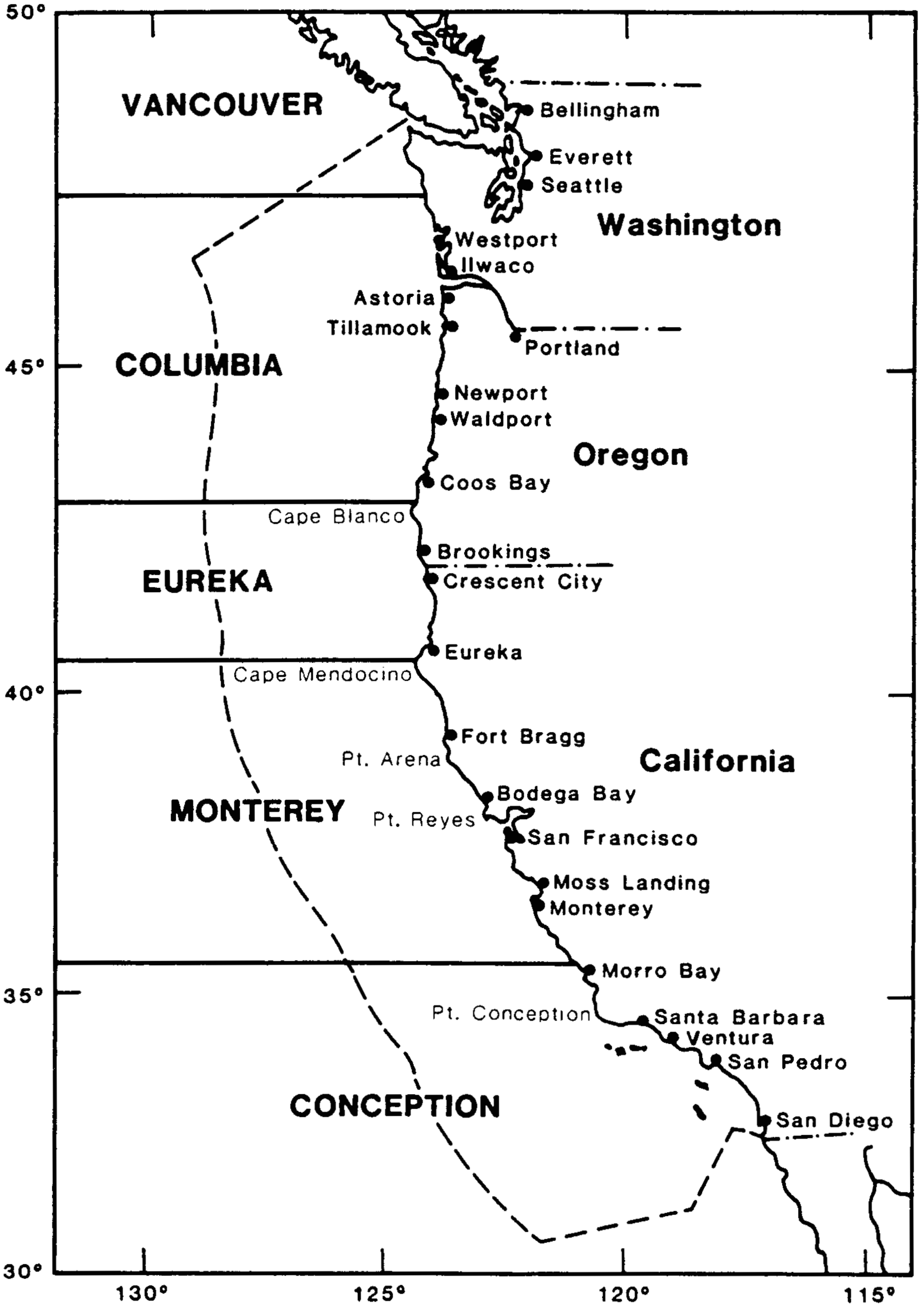

FIGURE 1. Location of Pacific coast fishing ports, landmarks and INPFC statistical areas.

Table 1
Total Allowable Catches for Groundfish Species, and Assumed Catch Constraints for Pink Shrimp and Dungeness Crab.

Species	Sub-Areas: Vancouver-Columbia	Sub-Areas: Eureka	Sub-Areas: Monterey	Total
	shorts tons			
Dover sole	15,318	8,816	5,510	29,644
Other flatfish	6,643	2,877	3,319	12,839
Code & lingcod	7,801	537	1,098	9,436
Widow rockfish	7,270	1,429	1,549	10,248
Other rockfish	13,563	2,965	9,461	25,989
Sablefish	3,502	1,924	1,776	7,207
Pacific whiting	—	—	—	209,380
Miscellaneous	10,113	1,309	1,591	13,013
Pink Shrimp	—	—	—	17,218
Dungeness crab	—	—	—	2,477

arrowtooth flounder, and others. In addition to the groundfish species, two important shellfish—pink shrimp and Dungeness crab—are included as alternatives to finfish.

Pacific coast trawlers display a wide range of sizes and vintages. For convenience we have designated five vessel length classes based upon Coast Guard registered length: (1) 40–49 ft., (2) 50–59 ft., (3) 60–69 ft., (4) 70–79 ft., and (5) 80–95 ft. Vessels in the two smaller classes are generally older, are often wooden-hulled, and make inshore trips of limited duration. Because they are less seaworthy in rough weather, the smaller vessels typically spend less time at sea during the winter. Intermediate-sized and large vessels are generally newer, steel-hulled vessels having greater cruising speed and range. They can more easily make trips of longer duration, are less hampered by rough weather, and can participate in a greater variety of fisheries.

The trawl fishery is both multispecies (harvests more than one species at a time) and multipurpose (participates in more than one discrete fishery). An important alternative for groundfish trawlers is pink shrimp fishing. Shrimping, which requires a special small-meshed trawl net, is seasonally concentrated in the spring and fall, and exhibits marked annual variation due to fluctuations in the shrimp populations. All three Pacific coast states have imposed regulatory restrictions on the shrimp fishery. These include maximum incidental groundfish landings, minimum size or count-per-pound standards, and season closures designed to protect egg-bearing females during November 1–March 31 (Pacific Fishery Management Council, 1981).

Another important alternative for trawlers is the "joint venture" Pacific whiting fishery in which midwater trawlers deliver fish directly to foreign-owned fish processing ships. Finally, some vessels replace their trawl nets with crab pots to participate in the Dungeness crab fishery during the late fall and winter. The amount of crab fishing by trawl vessels is usually not great, and represents a very small portion of the total catch in this highly cyclical fishery. Based upon these categories, six different fishing modes are identified: (1) multispecies groundfish trawling in the Vancouver-Columbia area, (2) multispecies groundfish trawling in the Eureka area, (3) multispecies groundfish trawling in the Monterey area, (4) single-species pink shrimp trawling, (5) single-species Dungeness crab pot harvesting, and (6) single-species joint venture fishing for Pacific whiting. The catch rates vary among these six modes, and for each mode they vary among seasons and vessel-size classes.

Model Specification

The mixed integer programming model maximizes economic surplus subject to constraints on total allowable annual harvest and constraints on vessel-weeks fished. The decision variables are: (1) 5 integer variables N_k for the number of vessels in each of the five size classes ($k = 1, \ldots, 5$) and (2) 120 real variables W_{jks} for the number of weeks fished by vessel size class k allocated to each fishing mode ($j = 1, \ldots, 6$) in each season ($s = 1, \ldots, 4$).

The model is specified as:

$$\text{Maximize } Z = \sum_{k} \Big(\sum_{js} \Big(\sum_{i} P_{ijs}a_{ijks} - C_k\Big)W_{jks} - F_kN_k\Big) \quad (1)$$

subject to:

$$\sum_{ks} a_{ijks} Wjks \leq Q_{ij} \text{ for all } i, j \tag{2}$$

$$\sum_{j} W_{jks} - N_k W^*_{ks} \leq 0, \text{ for all } s, k \tag{3}$$

where Z denotes economic surplus, P_{ijs} is the ex-vessel price of species i in mode j in season s, a_{ijks} is tons of species i in mode j harvested per week by a vessel of class k in season s, C_k is variable cost per week for vessels in size class k, F_k is fixed costs per year for vessels in size class k, Q_{ij} is the annual allowable catch for species i in mode j, and W^*_{ks} denotes the maximum number of weeks a vessel in size class k can fish during season s. The first constraint, equation (2), represents the limits on biological productivity, while the second constraint, equation (3), indicates the limits on harvesting activity by trawlers.

The technical coefficients a_{ijks} in the catch constraints reflect the assumed fixed-proportions joint-in-inputs harvesting technology for each groundfish mode. This assumption is fairly strong and possibly unrealistic. Trawl vessel operators undoubtedly do target upon various species by choice of timing, depth, towing speed, and gear configuration. The species mix actually observed in groundfish landings is an average of many different species mixes experienced during our base period. These patterns of landings represent complex economic decisions made jointly by fishermen and processors. As with all such economic decisions we would expect the species mix to change following any shift in expected fish prices, fishing costs, market demands, fish abundance or availability, and fishing regulations. Although we have not developed a model of fisherman/processor decision-making, we can expect some significant changes to affect fishing patterns in the long run. In particular, we anticipate that implementation of a limited access system would cause some systematic changes in fish stocks and relative profitability among vessel sizes. The consequent voluntary changes in targeting would raise profits from the level attainable with the initial pattern of targeting. The economic surplus achievable with centralized management, therefore, would be at least as large as that under the assumption of fixed fishing patterns. We conclude that the fixed coefficients technology will cause our model to underestimate the actual economic surplus available under limited access.

The mixed integer programming approach to optimum harvesting disregards several potentially important nonlinearities in the economic and biological relationships. The underlying bioeconomic model is one of static equilibrium. Thus fish prices do not respond to changes in annual harvests; input prices do not vary with total use; fish stock densities and harvest rates do not depend upon the level of harvest; and harvesting technology is unchanging. These conditions are inconsistent with standard market demand curves, input supply curves, and population dynamics models. Thus the results are strictly applicable only if the fishery is very small relative to both aggregate product demand and input supply, and if the range of total harvests analyzed is too small to significantly alter fish stock abundances. The Pacific coast trawl fishery probably comes close to satisfying the economic smallness criteria, but the annual harvests certainly affect fish abundance.

Our model assumes that the observed catch rates reflected in the technical production coefficients are consistent with the sustainable yield levels embodied in the annual harvest constraints. If the calculated optimum fishery does not exhaust all the biological harvest constraints, we would expect, in actual practice, the fish stocks to grow, the catch rates to increase, and the variable returns to fishing to increase. Because the model ignores this effect on catch rates, the model will understate the potential economic surplus.

Mixed integer programming analysis also ignores the historical pattern of operations in the fishery. In the words of Shephard and Garrod (1980), the linear programming method ''happily makes large changes in the pattern of allocation in pursuit of small advantages.'' Since changes from the status quo may be costly, these small advantages may be insufficient to justify adopting associated management policies that disrupt the fishing fleets. Our analysis is clearly subject to this criticism as well. We address this issue by computing maximum net economic values for a sequence of models in which the fleet is constrained to the base year vessel size distribution. This further constraint should reduce the presumed dislocations in the fishing fleet caused by a rapid shift to the optimum fleet configuration.

Model Implementation

Annual allowable harvests for the groundfish species established by the Pacific Fishery Management Council in 1985, as adjusted to reflect proportion taken by trawl gear during 1981–84, are adopted as overall catch constraints (Table 1). Lacking estimates of sustainable yield for pink shrimp and Dungeness crab, we take 1981–82 average total trawl catch levels as constraints. For pink shrimp the harvest constraint is close to the recent 12-year average pink shrimp harvest. The joint venture whiting fishery is initially constrained to the 1984 catch level. Higher and lower harvest constraints for whiting, shrimp, and crab are adopted to test the sensitivity of the model.

Technical production coefficients and constraints on amounts of fishing effort per vessel are based upon weekly catch records during 1981 and 1982 developed for the Pacific Coast Fisheries Information Network (PACFIN) research data base (Huppert et al., 1984). Technical coefficients for multispecies groundfish in each area and for coastwide pink shrimp and Dungeness crab are computed as average weekly catches by size class and season. Each "week" of fishing represents one calender week in

Table 2
Assumed Maximum Number of Weeks Fished per Vessel by Season and Size Class

Size Class	Winter	Spring	Summer	Fall	All Year
1	6.25	9.0	9.31	6.0	30.5
2	7.64	9.18	9.73	6.6	33.15
3	9.13	10.0	9.21	9.07	37.41
4	10.0	10.0	9.67	10.0	39.67
5	11.0	11.0	11.0	11.0	44.0

Table 3
Average Annual Fixed Costs and Weekly Variable Costs for Pacific Trawl Vessels (1984 dollars)

	Class 1	Class 2	Class 3	Class 4	Class 5
Weekly Variable Cost	$ 2638	3795	5518	5669	13,895
Annual Fixed Cost	45,990	49,639	78,535	83,952	110,550

which at least one commercial landing was recorded. Catch rates for Pacific whiting joint venture fishing were based upon information from private companies and financial reports. The assumed maximum number of weeks fished for vessels represents the average weeks spent fishing by the most active trawlers in each size class (Table 2).

Variable and fixed costs were estimated for each vessel size class using annual financial statements prepared for income tax purposes during 1980 to 1983 and using various other, secondary information sources (Table 3). Variable costs include the costs of fuel, oil, provisions, gear, crew and captain's share, payroll expenses, maintenance and repairs, ice, salt, bait, and miscellaneous. Crew and captain's labor payments are the average *share* earned, but we treat labor costs like a weekly wage. Fixed costs include capital costs (depreciation and opportunity cost of capital), hull and liability insurance, and taxes other than income taxes. Costs were adjusted to 1984-equivalent dollars using the GNP implicit price deflator for each year. Exvessel fish prices by area are averages for 1984 as observed in the PACFIN management data base (Table 4).

Variable costs, catch rates, and exvessel prices determine the net return per fishing week for each fishing mode and season for each vessel class. These net returns, which become the coefficients of the weeks fishing variables in the objective function (Equation 1), may be expressed as:

$$r_{jks} = (\sum_i P_{ijs} a_{ijks} - C_k) \tag{4}$$

Table 4

Exvessel Prices of Trawl-caught Fish and Shellfish. Price per ton in 1984 dollars. Source: PACFIN Management Data base

Species	Vancouver-Columbia	Eureka	Monterey	Joint Venture
Dover sole	456.4	483.3	459.5	
Other flatfish	561.2	553.0	552.0	
Cod & lingcod	501.3	536.0	515.2	
Widow rockfish	452.0	428.0	452.0	
Other rockfish	497.2	467.0	450.0	
Sablefish	402.8	377.3	335.0	
Whiting	138.0	126.7	182.5	149.4
Pink shrimp	———	1325.0	———	
Dungeness crab	———	2284.6	———	

As shown in Table 5 there are several negative values for these variable returns. It cannot be optimal to deploy fishing effort to categories yielding a negative variable return. A quick scan of Table 5 reveals among other things that no vessels in Class V should be included in the optimum trawl fleet, and that no class I vessels should enter the joint venture whiting fishery. Thus several conclusions can be drawn directly from examination of the coefficients of the fishing weeks variables.

The fishing week constraints do not prevent pink shrimp fishing during the closed season of November 1–March 31. Because recorded shrimp catch during that period is so low, however, the computed variable return per week from shrimping is negative during the winter quarter (January–March). Thus the programming model will not assign trawl vessels to the shrimp fishery during the prohibited winter period. The time resolution of the model does not allow us to examine periods of less than three months. Consequently, the fall portion of the shrimp fishing closure cannot be addressed directly. It is clear from Table 5, however, that the weekly return from shrimping falls markedly in the fall, making this an unlikely period for substantial fishing activity in the optimal program.

A baseline trawl fleet profit was calculated by inserting in

Table 5

Coefficients for Fishing Weeks in Objective Function of Programming Problem. Each entry equals the gross exvessel revenue minus variable cost per fishing week

	Vessel Size Class				
	I	II	III	IV	V
A. Vancouver-Columbia Area Multispecies Groundfish					
Winter	-91.4	-437.2	893.6	3956.1	-4206.1
Spring	1942.6	775.1	284.8	2923.5	-730.5
Summer	2152.9	3219.0	784.1	2533.3	-3469.8
Fall	551.3	875.9	-849.1	1145.4	-59.5
B. Eureka Area, Multispecies Groundfish					
Winter	209.8	-429.5	-112.1	2310.8	-10633.7
Spring	3903.2	1189.1	-1425.3	3089.8	-6723.4
Summer	2512.8	1248.9	260.6	3313.1	-2827.8
Fall	-652.2	-50.0	-1767.6	-52.4	-11394.8
C. Monterey Area, Multispecies Groundfish					
Winter	874.4	919.2	885.9	1878.8	-6953.0
Spring	783.9	719.8	-419.9	222.5	-9560.3
Summer	1720.1	1131.1	-475.0	1800.0	-7229.6
Fall	928.9	1069.3	-429.4	143.1	-12167.9
D. Pink Shrimp Fishing					
Winter	-1219.8	-2469.2	-3822.4	-1601.5	-13895.0
Spring	1880.2	2631.5	2908.6	4149.0	-4023.7
Summer	1231.4	2326.8	1716.0	2386.8	-11814.6
Fall	886.9	644.0	-443.7	412.5	-10661.9
E. Dungeness Crab Fishing					
Winter	-307.2	-1167.4	-2708.4	-528.8	-13894.9
Spring	-1266.8	-2561.0	-5289.9	-5069.2	-13894.9
Summer	1977.3	1482.7	-1429.0	2898.0	-13894.9
Fall	4033.5	3675.9	1929.3	6644.8	-8548.9
F. Joint Venture Whiting					
Spring	-2637.6	5287.9	6049.5	6993.5	-13894.9
Summer	-2637.6	5287.9	6049.5	6993.5	-13894.9

Table 6

Results of Mixed Integer Programming for the Pacific Trawl Fleet[a]

		Optimum fishery[c]		
	(1) Baseline fleet in 1984[b]	(2) JV takes whiting MSY	(3) 1984 JV harvest	(4) With no JV fishery
Number of vessels				
Class 1	106	0	0	0
Class 2	118	245	180	180
Class 3	138	0	0	0
Class 4	55	93	85	58
Class 5	12	0	0	0
Total number	429	338	265	238
Profit ($million)	−10.25	17.7	11.96	7.61
Proportion from:[d]				
Shrimp fishing	.324	.180	.267	.362
Crab fishing	.038	.081	.109	.143
JV fishing	.306	.475	.263	.000
Groundfish	.332	.264	.360	.495
Total weeks	11,763	11,034	9,041	8,054
Proportion in:				
Shrimp fishing	.218	.320	.380	.440
Crab fishing	.044	.042	.050	.060
JV fishing	.074	.280	.130	.000
Groundfish	.664	.358	.440	.500

[a] The solutions to the mixed integer programs were computed on an IBM-PC compatible computer using LP/MIP83, Version 5.00 copyrighted by Sunset Software, San Marino, California.

[b] The 1984 Baseline is not an optimum. The number and size distribution of vessels represents the 1984 fleet while the distribution of weeks fished represents the 1981–82 average. All prices and costs used in calculating profits are in 1984 dollars.

[c] All these assume the pink shrimp harvest constraint equals average 1981–82 catch (17,218 short tons).

[d] This is the proportion of operating profit (or net revenue) not economic profit. Fixed costs of vessels are not allocated among fisheries in calculating this proportion.

equation (1) the weeks fished in 1982, trawl fleet size in 1984, and the cost, price, and harvest rate parameters adopted for the model. The resulting estimate of economic surplus is \$ − 10.25 million (Table 6). This large negative value reflects a fishing fleet that was significantly overbuilt during the 1977 through 1982 period. Allowable rockfish harvests fell sharply during the latter half of the period due to cropping down of previously unfished populations of widow, yellowtail, and canary rockfish. Pink shrimp harvests also fell from a peak of 42 thousand short tons in 1978 to an average of 17 thousand short tons in 1981–82.

Results

Table 6 displays a summary of results from the mixed integer program. Assuming a 1984 level joint venture fishery, the optimum number of 265 vessels is a 38 percent reduction from the baseline trawl fleet in 1984. Optimum economic surplus is \$12 million, an increase of over \$22 million per year from the baseline fleet profit. Multispecies groundfish trawling accounts for slightly more than $\frac{1}{3}$ of the profit, shrimp fishing and joint venture whiting fishing each account for about one-quarter of the profit, and only one-tenth of the profit is from crab harvesting.

The size distribution of vessels in the optimum fleet differs markedly from the baseline. Absence of the largest and smallest vessel size classes in the optimum is not unexpected. Informal discussions with industry members and financial advisors suggested that the smaller vessels are now outmoded and that the largest class of vessel was too large to survive in the domestic Pacific coast fishery after the decline in rockfish harvests. The surprising absence of midsized, 60–69 ft. trawlers in the optimum fleet evidently occurs because the greater harvest rates achieved by these vessels as compared to 50–59 ft. vessels do not sufficiently counterbalance the proportionately greater increase in harvesting costs. The midsize vessels can be profitable in their own right, as shown in Table 5, when deployed in appropriate modes and seasons. But they are not profitable enough to be included in the optimum fleet.

The level and distribution of weeks fished by fishing mode and vessel size class (aggregated over seasons) also differ between the baseline and optimum fleets. The optimum total level of weeks fished is 9,041, a decline of about 31 percent from the baseline fleet to the optimum. Obviously, this fishing effort is concentrated in the second and fourth vessel classes: 63 percent in Class 2 and 37 percent in Class 4. Several other significant changes in fishing patterns occur in the optimization: the proportion of weeks assigned to pink shrimp trawling increases from 22 percent to 38 percent of the total; groundfishing trawling declines by almost one-third; and joint venture fishing for Pacific whiting almost doubles from 7 percent of the total to 13 percent.

A linear programming algorithm is used to calculate shadow prices for those species whose allowable harvests are binding constraints. These shadow prices represent the marginal value of additional harvestable quantities under the optimum fishery. An additional ton of widow rockfish sustainable yield, for example, would add $218 to the annual economic profit of the fishery in the Vancouver-Columbia area, nothing to the Eureka area fishery, and $533 to the Monterey area fishery. If the harvest constraints could be expanded through biological enhancement, these shadow prices would provide information useful to economic assessment of that enhancement. Since enhancement of groundfish species is generally considered infeasible, however, the shadow price has a different implication. The species with high shadow prices will be those attracting the most competition; they will command the highest prices under a transferable Individual Fisherman Quota system, or will require the closest enforcement effort under other forms of fishery management.

Sensitivity of the results to the joint venture whiting fishery is also shown in Table 6. Without a joint venture fishery and an average pink shrimp fishery, the optimum trawl fleet would have 238 vessels and would generate $7.6 million in profits annually. Adding a 1984-level joint venture fishery increases the optimum fleet to 265 vessels and the annual profit to $11.96 million. If the joint venture fishery grows to take the entire whiting maximum sustainable yield, the optimum fleet would have 338 vessels earning $17.7 million in profits. This wide variation indicates that the

Table 7

Optimum Economic Values when Fleet Is Reduced Sequentially and Size Distribution of Vessels Is Maintained at 1984 Base Level

Trawl Fleet	No. of Vessels	Fleet Profit	Total Revenue	Fixed Cost	Variable Costs	Total Weeks Fished
		$ millions				
1984 Base[a]	429	3.6	73.7	27.5	42.6	10,006
−10%	385	5.5	72.4	24.8	42.1	9,883
−20%	343	6.6	70.5	22.0	41.9	9,885
−30%	301	7.1	66.0	10.3	39.6	9,178
−40%	258	7.3	58.3	16.5	34.5	7,970
−50%	215	7.2	49.8	13.8	28.8	6,641
−60%	171	6.9	40.7	11.0	22.8	5,273
−70%	129	6.5	32.4	8.3	17.6	4,049
−80%	86	5.8	24.3	5.5	13.0	2,921
−90%	44	3.0	12.4	2.8	6.6	1,496

[a] Baseline is 1984 trawl fleet with an optimal allocation of fishing weeks across seasons, areas, and fishing modes.

model's sensitivity to assumed size of the joint venture fishery is quite high. Because the joint venture fishery employs foreign processing vessels, the likely size of that fishery depends on both domestic politics and foreign economic policies as well as domestic economic returns.

As noted above, a practical difficulty with adopting these results for fishery management policy is that the mathematical model ruthlessly ignores existing levels of investment and social commitment to the fishery. Instead of adopting an optimal fleet configuration, fishery managers may prefer to engage in a non-optimal fleet reduction program that improves economic performance with less social disruption. Table 7 examines one such non-optimal program in which the fleet size is sequentially reduced while the size distribution is maintained as initially observed in 1984. The results show that a fleet reduction of 40 percent can achieve a maximum of $7.30 million in economic surplus. This is a $4.7 million reduced profit from the overall optimum. Whether the decrease in social disruption entailed in this second-best fleet reduction program is "worth" the cost of reduced profit is not addressed by this study.

Sensitivity of the mixed integer programming solution to changes in the underlying technological and economic conditions was assessed by running the program with alternative constraints and parameters. The optimum fleet configuration and optimum number of weeks fished are robust to 10 percent changes in fixed costs, but is greatly affected by 30 percent variations. A 30 percent increase in fixed costs reduces the optimum fleet by 45 percent while a 30 percent decrease in fixed costs increases the optimum fleet by 21 percent.

Though it seems reasonable to assume pink shrimp harvests equal to the 1981–82 average of 17,218 short tons, historical fluctuations in the population make it important to assess the sensitivity of the results to variations in the shrimp resource. A 50 percent increase in the pink shrimp catch causes a 22 percent increase in fleet size, while a 50 percent decrease in shrimp causes a 12 percent decrease in optimum fleet size. Fleet profit and distribution of vessels among size classes were little affected. Similarly, the optimum fleet is little affected by 50 percent variations in the crab catch. Other sensitivity analyses show that increasing the maximum weeks of fishing for every size class by one week per season causes a very slight increase in optimum number of fishing weeks and a $1.56 million increase in profit. A combined increase in catch rates of 50 percent for widow rockfish and 30 percent for other rockfish causes only an 8 percent increase in fleet size and a $2.5 million increase in profit.

The results shown in Table 8 demonstrate the importance of maintaining a multipurpose fishing fleet. Columns 1–3 show the optimum vessel numbers, total profit, and weeks fished for three hypothetical specialized fishing fleets. These represent the solutions to three different mixed integer programming models, which assume in turn that the fishing fleet harvests only (1) multispecies groundfish and crab, or (2) pink shrimp, or (3) joint venture whiting (1984 level). Although each of these three separately optimized fleets could be profitable, the sum of the three fleets would contain 105 more vessels, would yield $3.78 million

Table 8

Comparison of Specialized and Multipurpose Optimum Trawl Fleets. Assuming 1984 JV harvest and 1981–82 average pink shrimp harvest.

	(1) Groundfish/ crab only	(2) Shrimp only	(3) JV whiting only	(4) Total for Three Fleets	(5) Change from Multipurpose Fleet[a]
Number of vessels					
Class 1	61	0	0	61	+61
Class 2	36	154	77	267	+87
Class 3	0	0	0	0	0
Class 4	42	0	0	42	−43
Class 5	0	0	0	0	0
Total number	139	154	77	370	+105
Profit ($million)	4.12	.217	3.85	8.18	−3.78
Weeks fished	4,724	3,929	1,449	10,102	+1061

[a] Col. (4) of this Table minus Col. (3) of Table 6.

less in annual profits, and would fish 1061 weeks more than an optimal multipurpose fleet. This result supports the provisional conclusion reported in Huppert (1979) that economically rational fisheries management needs to facilitate the operation of multipurpose fishing fleets. Multipurpose vessels are not only an economically rational adaptation to fluctuating fishing conditions by private operators but they are also economically efficient in aggregate. We conclude that a limited access program seeking to improve economic efficiency and/or fishing profits should not create divisions in the fleet, such as exclusive licensing for groundfish, shrimp, and joint venture whiting fishing.

Summary and Discussion

This mixed integer programming analysis of the Pacific coast trawl fishery yields approximate magnitudes of the economic surplus and fishing fleet size consistent with economically efficient harvest methods. Since the fixed, linear harvest technology specified does not consider possible adjustments in species targeting that would occur under a new management regime, the profit of roughly $12 million represents a lower bound to the potential economic surplus available from the trawl fishery. To achieve this economic surplus for the trawl fleet would require that other gear types be limited to their historic shares of groundfish harvests.

Additional important conclusions are apparent from the mixed integer programming results. First, maximum economic surplus occurs with a trawl fleet that is roughly 38 percent smaller than the fleet existing in 1984 with a 23 percent reduction in weeks fished. The exact size of the optimum fleet depends largely upon the size of the pink shrimp and joint venture whiting fisheries, but is also heavily influenced by variable fishing costs. The optimized fleet would consist of 50–59 ft. and 70–79 ft. trawlers. These results are relatively insensitive to variations in fixed costs, weeks available for fishing per year per vessel, crab catch rates, and rockfish catch rates. The optimum trawl fishery would not fully utilize the available sustainable yields of Dover sole, other flatfish, Pacific cod and ling cod, sablefish or miscellaneous species. It would fully or nearly completely utilize the sustainable yields of widow rockfish, other rockfish, pink shrimp and Pacific whiting to the extent permitted by joint venture fishery.

An important remaining question is whether the estimated surplus value earned under a hypothetical centralized manager could be generated under more traditional forms of economic organization. It is already widely understood that competitive fishing with open access property rules leads to zero net economic value. The estimated annual economic loss of $10 million under our baseline conditions is a reflection of this open access resource characteristic magnified by the rapid fleet expansion of the late 1970s combined with subsequent declines in pink shrimp and rockfish populations. Because of this economic disequilibrium, we would expect the trawl fleet, with or without a new access limitation system, to experience a painful contraction until aggregate fleet earnings return to a break-even level. The adjustment may be very sluggish, however, since the loss of financial capital associated with unprofitable vessel operations does cause rapid physical loss of vessels so long as operating costs can be covered by gross revenues. New owners and new financing arrangements will keep many vessels in operation long after the original owner has written off the investment.

A license limitation program could couple a freeze on new entry with a requirement that replacement vessels be no larger than the original vessels. As license holders retire, attrition could cause the fleet to shrink below the break-even level. Licenses would be issued to new replacement vessels once the fleet achieves an optimum size. Our experiment with this form of license limitation suggests that an optimum economic fleet would be 40 percent smaller than the fleet in 1984 and would earn a little over $7 million in profit. Even this estimate is probably too optimistic. Economic theory and actual experience in the British Columbia salmon fishery (Fraser, 1979) suggest that the emerging fishing profits under a license limitation system will induce fishermen to dissipate profits through costly vessel upgrading. Open access competition for fish would continue among the limited number of operators. Anderson (1985) has argued that a license-limited fishery may settle into an economic equilibrium that does generate positive economic profits, but that these profits will fall short of the maximum possible under a centralized owner/manager.

Individual Transferable Quotas (ITQ) afford a more promising means to generate the potential economic surplus from the trawl fleet. Christy (1973), Moloney and Pearse (1979), and others have argued that an efficiently operating ITQ system could mimic the efficiency of a free market system. This approach would require an altered fisheries law enforcement system and necessitate enhanced legal standing for private rights in fish stocks. New Zealand has recently adopted an ITQ system for deepwater groundfish trawling. Holders of these ITQs will have private economic incentives more consistent with optimum social use of the fishery resources. Such a radical break with traditional fishery systems might entail significant disruptions in private business operations and government bureaucracies. Given the costs of such disruption the potential $12 million harvesting profit may be too small to justify changing the property institutions in the fishery. But the adjustment costs would be transitory, and further investigation of these should precede any decisions on limiting access.

Acknowledgments

The authors wish to thank Ms. Cynthia Thomson, Samuel Herrick, and an anonymous referee for helpful comments.

References

Anderson, L. G. 1985. Potential economic benefits from gear restrictions and license limitation in fisheries regulation. *Land Economics* 61: 409–418.

Blomo, V. J., J. P. Nichols, W. L. Griffin, and W. E. Grant. 1982. Dynamic modeling of the Eastern Gulf of Mexico shrimp fishery. *Amer. J. Agr. Econ.* 64: 475–482.

Brown, B. E., J. A. Brennan, and J. E. Palmer. 1979. Linear programming simulations of the effects of bycatch on the management of mixed species fisheries off the northeastern coast of the United States. *Fish. Bull.* 76: 851–860.

Christy, F. T. Jr. 1973. Fishermen quotas: a tentative suggestion for domestic management. *Occasional Paper No. 19, Law of the Sea Institute, University of Rhode Island.*

Drynan, R. G., and F. Sandiford. 1985. Incorporating economic objectives in goal programs for fishery management. *Mar. Res. Econ.* 2: 175–195.

Fraser, G. A. 1979. Limited entry: experience of the British Columbia salmon fishery. *J. Fish. Res. Board Can.* 36: 754–763.

Huppert, D. D. 1979. Implications of multipurpose fleets and mixed stocks for control policies. *J. Fish. Res. Board Can.* 36: 845–854.

Huppert, D. D., C. J. Thomson and S. Iacometti. 1984. A report on the 1981 PACFIN research data base. NOAA/NMFS Southwest Fisheries Center Administrative Report LJ-84-03. La Jolla, Calif.

Huppert, D. D., and D. Squires. 1986. Potential economic benefits of limited access in the Pacific coast trawl fishery: a linear programming approach. *Nat. Mar. Fish. Ser. Admin. Report LJ-86-01.*

Moloney, D. G., and P. H. Pearse. 1979. Quantitative rights as an instrument for regulating commercial fisheries. *J. Fish. Res. Board Can.* 36: 859–866.

Overholtz, W. S. 1985. Managing the multispecies otter trawl fisheries of Georges Bank with catch optimization methods. *North Am. J. Fish Man.* 5: 252–260.

Pacific Fishery Management Council. 1981. Draft fishery management plan for the pink shrimp fishery off Washington, Oregon and California. Portland, Ore.

Rettig, B., and J. Ginter. 1978. *Limited Entry as a Fishery Management Tool.* Seattle: University of Washington Press.

Rettig, R. B. 1984. License limitation in the United States and Canada: an assessment. *North American J. Fish Mgmt* 4: 231–248.

Shephard, J. G., and D. J. Garrod. 1980. Modelling the response of a fishing fleet to changing circumstances, using cautious non-linear optimization. *J. Cons. Int. Explor. Mer.* 39: 231–238.

Siegel, R. A., J. J. Mueller, and B. J. Rothschild. 1979. A linear programming approach to determining harvesting capacity: a multispecies fishery. *Fish. Bull., U.S.* 77: 425–433.

Stokes, R. L. 1979. Limitation of fishing effort: an economic analysis of options. *Marine Policy* 3(4): 289–301.

Young, O. R. 1983. Fishing by permit: restricted common property in practice. *Ocean Development and International Law Journal,* 13(2): 121–170.