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Fleet Restructuring, Rent Generation, and the Design of Individual Fishing Quota Programs: Empirical Evidence from the Pacific Coast Groundfish Fishery

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Keywords
Individual fishing quotas, scale and technical efficiency, fleet restructuring

Disciplines
Agricultural and Resource Economics | Animal Studies | Regional Economics

Comments
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JEL Classification Codes   Q2, D24.

Introduction

The Pacific Coast groundfish fishery (PCGF) is currently managed under a controlled access program. Commercial harvesting activities are regulated with vessel entry restrictions, gear restrictions, area closures, seasonal closures, and bimonthly (per-vessel) catch limits. These regulations are required to prevent overfishing of groundfish stocks, in particular species which have been identified as overfished or subject to overfishing. Controlled access management does not align fleet harvesting capacity with catch targets, is costly to administer, and in the case of Pacific groundfish introduces incentives to discard fish at sea (Branch, Rutherford, and Hilborn 2006). Overall, the controlled access...
The program has not met key management objectives, which in turn has prompted calls for an alternative management approach that might improve economic and biological conditions in the fishery.

In this article, we examine the economic implications of adopting an individual fishing quota (IFQ) management program for the limited entry trawl component of the PCGF, which accounts for about 70% (on an ex-vessel revenue basis) of the groundfish landed on the Pacific Coast (California, Oregon, and Washington) of the United States. Our specific goal is to provide an *ex ante* estimate of changes in fleet structure and profitability that are expected if controlled access is replaced by IFQs. For reasons of data availability, we focus our analysis on the non-whiting component of the limited entry trawl fleet, which hereafter for simplicity is referred as the *groundfish fleet*.

This analysis is particularly timely because the Pacific Fishery Management Council voted to begin consideration of an IFQ program for the Pacific Coast limited entry trawl groundfish fishery in 2003 and recommended trawl rationalization through an IFQ program in November 2008. At the June 2009 meeting, the Council completed a series of trailing actions on eligibility to own quota, accumulation limits, a set aside for adaptive management, and miscellaneous clarifications. Over the remainder of 2009, the National Marine Fisheries Service is expected to begin drafting regulations, and Council staff will finalize the draft amendments package. Fishing is expected to begin under IFQs in 2011.

The conceptual approach follows recent work by Weninger and Waters (2003) and Singh, Weninger, and Doyle (2006). In a first step, we use data on operating expenses and catch of groundfish vessel operations to estimate the cost inefficiency under the current management program and calibrate vessel level harvesting costs for simulation purposes. Exploiting the economic incentives implicit in IFQ operating rules for groundfish trawlers, we use the calibrated costs to predict the number and type (length class) of vessels expected to participate in an IFQ-managed groundfish fishery. The analysis allows us to estimate cost savings and resource rents expected to emerge in the PCGF, and also predict the vessel length classes that are most likely to remain active under IFQ management.

Our results suggest that (with landings held at 2004 levels) the current groundfish fleet, which consisted of 117 vessels in 2004, will be reduced by roughly 50–66% to 40–60 vessels under an IFQ program. The reduction in fleet size implies cost savings of $18–$22 million for the year 2004 (most recent year of the data). Vessels that remain active will, on average, be more cost efficient and will benefit from economies of scale that are currently unexploited under controlled access regulations in the fishery. The cost savings estimates are significant, amounting to 60% of costs incurred currently, suggesting that IFQ management may be an attractive option for the PCGF. We find that mid-sized boats, 60–70 feet in length, are relatively cost efficient and therefore most likely to remain active under the IFQ management program; smaller (40–50 feet) and larger vessels (80 feet and above) are likely to exit the fishery.

Our analysis reveals, however, that projected cost savings are sensitive to the design elements of the IFQ program. In particular, we show that restrictions on the total quota that can be harvested by individual vessels, or restrictions on quota trading across vessel length classes, can significantly reduce the estimated benefits (cost savings) of switching to IFQs. Our estimates suggest that benefits decline by roughly $3.80 million (18.4%) per year if a 1% cap on quota ownership at the vessel level is imposed, and by as much as $2.14 million (10.4%) per year under restrictions on harvest permit trading across vessel classes.

Results further show that program design elements have implications for the capital types and vessel length classes that will remain active in an IFQ-managed groundfish

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1. The regulatory regime in other portions of the Pacific Coast groundfish fishery, including the limited entry fixed-gear fleet and the open-access fleet, is assumed to remain unchanged. We do not consider changes to the whiting fishery.
2. Our model predicts equilibrium fleet structures and economic rent under IFQ management. The transition from current conditions to IFQ-equilibrium conditions are likely to take time. An analysis of this transition period is beyond the scope of this paper.
Pacific Groundfish Quota Program

As one might expect, tight harvest quotas on individual vessels favor smaller boats due to their lower fixed costs of operation. Restrictions on permit trading across vessel classes will keep vessels active that would otherwise exit the fishery and will reduce resource rents that are generated under the IFQ program.

A related finding concerns the mode of rent collection to administer the IFQ program. Current program designs include 100% coverage of groundfish trips by on-board observers, with costs collected from participants in the IFQ program. The way these costs are collected has crucial implications for the operational fleet structure. Charging vessel operators directly for observer costs on a days-at-sea basis favors larger vessels. Large vessels harvest more fish per day than small vessels and thus incur lower observer cost per landed pound. Furthermore, collecting observer costs from active boats lowers profits, which leads to a smaller IFQ-regime fleet and lower fleet harvests. If observer costs are collected through landings taxes, both the harvest quantity as well as the fleet size decline. The harvest decline, however, occurs only for the species with lower dock-side prices. When these taxes are uniformly levied on a per-pound basis, the effective price for low-value species drops relatively more, and its harvest decline is larger. Since smaller boats run closer to their physical harvest capacities, their costs (inclusive of taxes) rise relatively more under landing taxes. Once again, as a result landing taxes tilt fleet size toward larger vessels, albeit to a lesser extent than under the days-at-sea basis.

Our article adds to a growing literature that has emphasized the gains in economic efficiency available under IFQ management programs (e.g., Grafton, Nelson, and Turris 2005; Weninger and Waters 2003; Casey et al. 1995). We derive new insights concerning the role of IFQ program design on the nature of fleet composition and rent generation. The results provide guidance for policy makers who must weigh the efficiency gains and distributional impacts that accompany a switch to rights-based fisheries management.

The next section presents a conceptual model of the IFQ fishery and highlights the economic incentives that underlie an IFQ management program. We then summarize our analysis of inefficiency under the PCGF controlled access management program and present an overview of our calibration of groundfish harvest costs. A detailed discussion of the data and econometric methods used in calibrating the model is presented in an Appendix. We then investigate the equilibrium fleet structure and resource rents under an IFQ program in a dynamic fishery where total available harvests are uncertain. Key findings are summarized in a concluding section.

The Model

We will consider a multiple-species IFQ management program. To fix ideas, we begin with a static and deterministic analysis; fleet structure in a dynamic uncertain harvesting environment is examined below.

The manager issues species-specific permits which grant their owner a right to harvest specified quantities of fish. Production periods are distinguished with a subscript $t$. The total permits issued and thus the total allowable harvest in period $t$ is denoted $Q_{mt}$ for

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3 Current law limits the Federal government’s ability to collect fees to a maximum of 3% of the ex-vessel value of fish harvested under the program, regardless of the actual cost of the program.

4 Grafton (1992) studied the impacts of alternative rent capture methods in rights-based fisheries. Grafton (1994) examined the effects of fish price uncertainty. To our knowledge, the impacts of total allowable catch uncertainty and rights-based program design on fleet composition, harvesting activity, and rent generation has not been examined.

5 Amendment 20 to the Groundfish Fishery Management Plan, which is currently in development, allocates harvest rights as shares of total allowable catch levels. Modeling harvest rights as quantities simplifies our presentation and has no effect on the results.
species $m=1,...,M$. The biomass in the fishery is denoted $X_{mt}$ for species $m$. Catch cannot exceed biomass and thus, $Q_{mt} \leq X_{mt}$ for all $m$.\(^6\)

Denote the quantity of species $m$ fish landed by vessel operation $i$ in period $t$ as $q_{imt}$. We assume that the manager is able to monitor the total landings in the fishery. Total landings cannot exceed total available permits:

$$\sum q_{imt} \leq Q_{mts} \text{ for all } m = 1,...,M, \text{ for all } t. \tag{1}$$

To simplify notation we will hereafter consider a representative production period. We also let $Q = (Q_1,...,Q_M)$ denote the vector of total harvest permits, $X = (X_1,...,X_M)$ denotes the vector of stocks, $q_i = (q_{i1},...,q_{IM})$ denotes the harvest vector of vessel $i$, and $P = (p_1,...,p_M)$ denotes the vector of dockside prices.

Variable fishing costs for operator $i$ are defined over the harvest vector $q_i$:

$$c_i(q_i,k_i,X) = \min_z \left( w'z \mid (z \text{ can harvest } q_i \text{ given } k_i, X) \right),$$

where $z$ is a vector of variable factors of production (e.g., fuel, labor, bait, and ice), which we assume are purchased competitively at price vector $w$, and $k_i$ denotes the capital employed by vessel operation $i$. The subscript on variable costs captures heterogeneity in cost efficiency of individual vessel operations. We explicitly allow for heterogeneity due to the vessel skipper’s efficiency and cost differences across vessel sizes or lengths. Variation in skipper skill levels can be important in fisheries, and, therefore, may be a key source of cost savings under IFQ management (Squires and Kirkley 1995; Weninger and Waters 2003). The implications of IFQ operating rules on the cost efficiency of different vessels lengths are of particular interest and are investigated thoroughly below.

It is useful to contrast minimum costs under IFQ management with costs under a controlled access management program. Under the latter, the maximum number of active vessel operations is fixed through entry permits. Because limiting the number of vessels alone does not ensure the harvest constraint in equation 1 is met, additional restrictions on vessel harvesting activities are required. In general, a combination of entry permits along with restrictions on harvesting operations will not align fleet size with individual vessel harvests in a cost-efficient manner.

IFQ management, on the other hand, aims to control directly the total harvest in the fishery. We assume that there are no restrictions on IFQ ownership and that the IFQ program is closed in the sense that harvest of all fish species requires IFQ permits (the implications of caps on quota ownership is considered below). These assumptions imply:

$$c_i^{IFQ}(q_i,k_i,X) \leq c_i^{LE}(q_i,k_i,X).$$

In other words, harvesting costs for an identical harvest vector $q_i$, for a given level of capital, stock abundance, and skill level, can only decline under IFQ management as various restrictions (e.g., gear restrictions, bimonthly landings restrictions) utilized under controlled access management are eliminated.

The total profit for vessel operation $i$ is given as $\pi_i(q_i,k_i,X) - f_c$, where $f_c$ denotes the fixed cost of operation $i$, and $\pi_i(q_i,k_i,X)$ is the variable operating profit:

$$\pi_i = pq_i - c_i(q_i,k_i,X).$$

\(^6\) Managers may face additional constraints on harvest choices. For example, the Magnuson Stevens Fisheries Conservation and Management Act prohibits setting harvest levels that exceed overfishing levels (see MSFCMA 2007).
The decision to be an active participant in the IFQ-managed fishery must consider two opportunity costs: the cost of the vessel capital, $f_c$, and the harvest permit user cost. The latter cost exists with IFQ management because harvest permits are tradable. To see this formally, suppose the manager issues species-specific permits that grant the right to harvest $Q_m$ units of species $m$ fish, $m = 1,...,M$. The owner of harvest permits is the residual claimant of the excess profit that can be generated by harvesting and selling fish. High-cost vessel operations will earn less profit than low-cost vessels and will face an incentive to sell their permits and exit the fishery.

Assume that a well-functioning permit trading market emerges under IFQ management. Let $r = (r_1, r_2, ..., r_M)$ denote the vector of permit lease prices. For all active vessel operations in the IFQ fishery the following conditions must hold in equilibrium:

$$\pi_i(q_i, k_i, X) - f_c - r_i q_i \geq 0,$$

$$\frac{\partial c_i}{\partial q_m} = p_m - r_m, \text{ for all } i$$

$$\sum_{m \in N_{IFQ}} q_{m} = Q_m \text{ for } m = 1,...,M$$

where $N_{IFQ}$ denotes the set of active vessel operations.

The first condition states that all active vessels must earn non-negative profits, where profits explicitly include the per-period permit holding cost, $r_i q_i$. The second condition in equation 2 ensures that the gains from permit trades among active vessel operations are exhausted. The third condition is simply a restatement of equation 1.

The conditions in equation 2 reveal three sources of cost savings are expected when controlled access management is replaced with IFQs. First, lifting the restrictions on harvesting activities will lower harvesting costs for all vessels. Second, per-unit harvesting costs are expected to fall under IFQs as the harvesting responsibilities gravitate to the most cost-efficient operators in the vessel population. Third, vessels that are active under IFQs will exploit available economies of scale and scope in production.

**Efficiency Analysis and Cost Calibration**

Our empirical analysis has two goals. The first is to measure the extent of harvesting inefficiency in the PCGF under the controlled access management program. The second goal is to estimate a structural model of trawl vessel harvesting costs that can be used to simulate the impacts of a switch to IFQ management. This section provides a brief overview of the data and econometric methods used. Further details are presented in the Appendix.

Our data are from PacFIN (the Pacific Coast Fisheries Information Network) and a cost and earnings survey of limited entry trawl vessel owners conducted by the National Marine Fisheries Service and Pacific States Marine Fisheries Commission for the 2003 and 2004 groundfish harvest seasons. There are 111 unique vessels operations and a total of 130 annual cost and landings observations in our data. Since it was not feasible to estimate our model with the over 80 different species of groundfish reported by PacFIN, we aggregated groundfish into three groups based on location of catch, season of catch, and per-pound value of catch. Our analysis aggregates the over 80 species of groundfish reported by PacFIN into whiting, the DTS group (Dover sole, thornyheads, and sablefish), and non-DTS species.
A stochastic cost frontier approach is used to estimate differences in variable harvesting cost efficiency. Costs for vessel operation \( i \) are assumed to follow:

\[
c_i(q,k,X) = v_i c(q,k,X) \epsilon,
\]

where \( c(q,k,X) \) is the deterministic cost frontier, \( v_i \geq 1 \) is a measure of cost inefficiency for operation \( i \), and \( \epsilon > 0 \) reflects the stochastic component of the cost frontier. To estimate equation (3) we require a functional form for variable costs and distributional assumptions for the efficiency and stochastic components.\(^7\) An exponential function is specified for variable costs, \( c_i(. \) = \( \exp(.) \). The exponential function is simple, parsimonious, and strictly positive—properties that offer advantages for our simulation exercise.\(^8\) Distributional assumptions for the inefficiency and the stochastic components of costs follows Hadri (1999) (see Appendix for additional discussion).

The cost function estimation results conform to expectations with one exception; results indicate that the fuel price coefficient is negative with \( p \)-value = 0.072. We are fairly confident that this perverse sign is the result of aggregation in our fuel price data (see Appendix for additional discussion).

**Cost Inefficiency**

Following Jondrow et al. (1982), we calculate the conditional expected value \( \hat{v}_i = E[v_i | v_i + \epsilon] \). Cost inefficiency is then obtained as \( \exp(\hat{v}_i) \). Figure 1 reports vessel/year-specific efficiency scores along with 95% confidence intervals (Horrace and Schmidt 1996). The results suggest substantial cost inefficiency for a small portion of the fleet, although the lower bound of the confidence interval lies close to the frontier value of unity for most observations. The inefficiency analysis suggests that cost savings in the form of pure efficiency gains can be expected under an IFQ management program, as the bulk of the harvest responsibilities are transferred to the most productive vessels in the fleet.

**Scale Economies**

We next consider cost savings expected under the IFQ management program due to unrealized economies of scale. A useful measure of multi-output economies of scale is given in Panzar and Willig (1977):

\[
S_i = \frac{c_i(q,k,X) + f_i}{\sum_{q_i} \partial c_i(q,k,X)/\partial q_i}.
\]

In the above, \( S_i > 1 \) indicates economies of scale exist at harvest vector \( q \), whereas \( S_i < 1 \) indicates diseconomies of scale at \( q \). \( S_i = 1 \) indicates constant returns at harvest vector \( q \).

We calculate \( S_i \) for all vessels in our sample using estimated variable plus fixed operating costs (see Appendix). We divide the sample into vessels that operate in a region

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\(^7\) Kumbhakar and Knox Lovell (2000) provide a comprehensive discussion of stochastic frontier theory and estimation methods.

\(^8\) Linear and log-log specifications provided inferior fits to our cost data. It should be noted that the exponential function imposes the structural property of homotheticity. Although beyond the scope of the current study, a flexible functional form could be used to test the structural properties of groundfish harvest technology (Kirkley and Strand 1988).
of increasing returns, constant returns, and decreasing returns to scale. The results indicate that of the 62 sample vessels observed in 2003, 3 operated in a region of decreasing returns, 8 operated at constant returns, and 51 operated in a region of increasing returns to scale. The 2004 sample observations indicate that 5 vessels operated in a region of decreasing returns, 12 operated at constant returns, and 51 operated in a region of increasing returns to scale. For vessels operating under increasing returns, average cost per unit of harvest will decline if the scale of production is increased. Note that this is precisely what is predicted to occur in the groundfish fishery as the current system of bimonthly catch limits is replaced with IFQs.

In sum, the analysis of scale efficiency suggests fleet downsizing under the proposed IFQ management. As more catch is consolidated onto fewer vessels, average costs per landed pound of groundfish is expected to fall due both to increases in scale economies and a redistribution of the harvest from the least to the most efficient vessels in the fleet. The combined effect will be a reduction in the total costs required to harvest the aggregate groundfish catch in the fishery, or alternatively an increase in the resource rent generated in the fishery.

**Potential Cost Savings under IFQ Management**

We next use the model to assess the potential cost savings in the fishery if the controlled access management program is replaced with IFQs. Our approach is to estimate the minimum efficient scale of production for different vessel types (each vessel type is a different length). We then calculate average harvesting costs for representative vessel types (lengths) that operate at minimum efficient scale of production and attain a reasonable level of cost efficiency. An individual vessel efficiency level of \( \exp(v_i) = 1.215 \) is
assumed, which is the median value estimated from our sample. The resulting cost estimates are then compared to estimates of the actual costs incurred by our sample vessels under the controlled access program to obtain an estimate of the potential for cost savings under IFQs.

Table 1 reports estimates of minimum efficient harvest scale, calculated as the harvest that minimizes ray average cost (RAC), and associated RAC, for six vessel length classes. The table also reports estimates of the fleet costs, cost savings, and fleet sizes under a scenario in which the 2004 groundfish catch is harvested by a fleet consisting of cost efficient operations of different length classes (see Appendix for details). The results can be viewed as a first approximation to the fleet restructuring and efficiency gains expected in the PCGF under IFQ management. We estimate the harvest cost savings as the difference between the sample RAC of $0.657 per landed pound and RACs reported in table 12. Predicted costs and cost savings are reported in 2004 dollars.

<table>
<thead>
<tr>
<th>Catch/Vessel and Harvest Cost</th>
<th>Cost Savings and Fleet Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catch/Vessel</td>
<td>(MES)</td>
</tr>
<tr>
<td>Len.</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>90</td>
</tr>
</tbody>
</table>

Note: MES is minimum efficient scale, RAC is ray average cost. Fleet size is calculated by dividing the 2004 groundfish harvest by the RAC-minimizing harvest.

The results in table 1 can be interpreted as follows. Consider the 40-foot representative vessel length. If the entire PCGF fleet were made up of 40-foot vessels, the fleetwide costs are predicted to be $20.180 million in 2004. This represents a cost saving predicted at $18.609 million, which represents 49.97% of the costs estimated to have been incurred in 2004. To harvest the entire 2004 catch (excluding whiting) with a fleet consisting entirely of 40-foot boats, 119 vessels would be utilized. Moving to larger vessels, the results indicate that the cost savings are largest for fleets consisting of 50- and 60-foot vessels. Cost savings under these vessel lengths are in the range of $23 million, which is almost 60% of the 2004 costs. The number of vessels required to harvest the 2004 catch is estimated at 70 and 45 for the 50- and 60-foot length classes, respectively. PacFIN data reveal that 117 non-whiting groundfish limited entry trawlers were active in 2004 (number excludes 26 vessels that targeted primarily whiting). Correspondingly, the results in table 1 indicate that considerable fleet downsizing is expected under IFQ management as vessels consolidate the harvest and exploit available economies of scale.

Further calculations provide some additional insights on the economic conditions under controlled access regulations. Assuming a 10% annual return to the vessel capital investment, estimates indicate that the 2004 groundfish fleet incurred a total cost of

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9 RAC is defined as $c(\lambda q, k, X)/\lambda$ for scalar $\lambda \geq 1$ (see Baumol, Panzar, and Willig 1982).
$38.789 million. The PacFIN data indicate fleetwide revenue at roughly $36.275 million in 2004, and, therefore, fleetwide losses of $2.514 million. Based on a lower 5% annual return to the vessel capital, the results suggest that the groundfish fleet merely broke even in 2004; i.e., dockside revenues were offset by the fleet-wide total harvesting costs. Negligible resource rents under controlled access regulations are consistent with what one would expect, which lends credibility to our cost calibrations. Nevertheless, the simulation results that follow should be interpreted in the context of data constraints that the calibration exercise encountered.

**Fleet Structure and Fishery Value under IFQ Management**

This section predicts the equilibrium fleet structure, harvesting costs, and fishery rents that are expected to emerge under an IFQ management program. Based on the above analysis of the cost and earnings survey data, fleet size and costs are expected to decline. The magnitude of these changes will depend on the form that the IFQ program takes; e.g., the species that are included in the IFQ program, restrictions on the transferability of harvesting permits, or the approach used to recover program administrative costs. It will also be affected by the TAC levels announced by the fishery managers and the randomness in the announced TACs over time. This section first estimates a random harvest model which captures the randomness in TAC that is likely to prevail in the IFQ-managed fishery. We combine the estimated harvest costs and random harvest model into a dynamic model of the PCGF. The model predicts equilibrium fleet structure, harvesting costs, and rents expected under uncertain TACs.

**Random Harvest Model**

Growth, natural mortality, and thus total stock abundance and allowable harvests are influenced by random fluctuations in the marine environment. Changing environmental conditions are likely to cause fluctuations in the TAC targets in the PCGF. Because variation in the TAC from year to year has implications for fleet size and fishing profits, we require a model that reflects the normal variability of these factors. A parsimonious biological model that captures abundance and growth for all harvested groundfish species (more than 80 in all) is difficult to conceive. We assume simply that the management rules which determine annual TACs are not altered significantly by the introduction of an IFQ program. We approximate temporal adjustments in groundfish TACs from observed harvests reported in the 1994-2006 PacFIN data. Specifically, we assume that the TAC of groundfish species \( m \) follows:

\[ Q_m = z_m Q_m, \quad (4) \]

where \( Q_m \) is the average TAC for species \( m \), and \( z_m \) is a unit-mean multiplicative random shock. The random shock \( z_m \) is contained in the interval, \( [z_m, \bar{z}_m] \), where \( 0 < z_m < \bar{z}_m \).

Species-specific shocks follow a first-order autoregressive process:

\[ z_m' = \varsigma_m + \rho_m z_m + \eta, \quad m = 1, \ldots, M, \quad (5) \]

where \( \rho_m \in [-1,1] \), \( \varsigma_m + \rho_m = 1 \), and \( \eta \) is an independently and normally distributed disturbance with zero mean and finite variance \( \sigma^2_\eta \). Hereafter, we refer to equations 4 and 5 as the harvest transition model.
To estimate the parameters of the harvest transition model, we obtained annual landings data from the PacFIN database for 1994-2006. Annual landings for the groundfish fleet in the PCGF for $m = 6$ species groups are shown in Figure 2.

Visual inspection of historical landings indicates a declining catch for some groundfish species (e.g., DTS and non-DTS species groups). To ensure that catch trends do not influence the estimates of the harvest transition model, we assume the period $t$ annual landings of species group $m$ fish follows:

$$Q_{m,t} = a_m + b_m t.$$

The parameters of the model $\zeta_m$, $\rho_m$, $a_m$, $b_m$, $m = 1, ..., M$ are estimated using feasible generalized non-linear least squares following Judge et al. 1985 (see pp. 483-90).

Table 2 reports the parameter estimates along with the actual and predicted harvest for 2004. We see that the harvest of each species is positively serially correlated. It is also seen that the magnitudes of the $\zeta_m$ and $\rho_m$ do not much differ across species groups. We estimated a restricted version of the shock transition equation in equation (5) in which $\zeta_m = \zeta$ and $\rho_m = \rho$ for all $m$. Based on the results of a likelihood ratio test, we failed to reject the null hypothesis that the random shocks follow a common process (the chi-square statistic is 0.071 with critical value 11.07). The results of the restricted model yield estimates of $\zeta = 0.698$, $\rho = 0.303$, and $\sigma = 0.300$. 

Figure 2. Landings by Major Species Groups: 1994-2006
Our model of dynamic fleet adjustment closely follows Singh, Weninger, and Doyle (2006). The dynamic program is summarized by the following Bellman equation:

\[
V(z, k_1, k_2, \ldots, k_n) = \max_{\{k_j, q_j\}} \left\{ \sum_{j=1}^{n} k_j \left[ \pi_j(q_j, k_j, X) - fc_j \right] - \sum_{j=1}^{n} p_j I_j + \beta \cdot E_{z' | z} V(z', k'_1, k'_2, \ldots, k'_n) \right\},
\]

subject to: \( k'_j = k_j + I_j, \ j = 1, \ldots, n \),

and subject to equations 4 and 5. In the above functional equation, \( \beta \) is the discount factor; \( k_j \) denotes the number of vessels of length class \( j \); \( q_j \) denotes the harvest vector vessel class \( j \) vessel; \( fc \) is the fixed cost of a vessel of class \( j \); \( \pi(\_\_) \) is the variable harvesting profit; \( I_j \) is the number of new boats of class \( j \) inducted in the fleet and \( p_n \) is the class \( j \) vessel price. Finally, \( E_{z' | z} \) is the expectation of the one-period-ahead shock conditional on the current shock.

Standard numerical techniques are employed to solve the above program by guessing an initial \( V(\_\_) \) and then iterating it to convergence (Judd 1998). The reader can also refer to Singh, Weninger, and Doyle (2006) for technical details.

### Table 2
Harvest Transition Model: Parameter Estimates

<table>
<thead>
<tr>
<th>Species</th>
<th>( \varsigma_m )</th>
<th>( \rho_m )</th>
<th>( Q_{2004} )</th>
<th>( \tilde{Q}_{2004} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whiting</td>
<td>0.49</td>
<td>0.51</td>
<td>197.69</td>
<td>178.98</td>
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<tr>
<td>DTS</td>
<td>0.53</td>
<td>0.47</td>
<td>23.25</td>
<td>24.23</td>
</tr>
<tr>
<td>Non-DTS</td>
<td>0.44</td>
<td>0.56</td>
<td>21.24</td>
<td>24.45</td>
</tr>
<tr>
<td>Crab</td>
<td>0.78</td>
<td>0.22</td>
<td>8.02</td>
<td>7.09</td>
</tr>
<tr>
<td>Shrimp</td>
<td>0.68</td>
<td>0.32</td>
<td>5.11</td>
<td>14.43</td>
</tr>
<tr>
<td>Other</td>
<td>0.74</td>
<td>0.26</td>
<td>1.46</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Note: Total harvest in 2004 is in millions of pounds.

**Dynamic Model of Fleet Structure and Fishery Rent**

This section presents the results from the dynamic model of the IFQ-managed groundfish fishery. We first examine fleet structure, costs, and rents under a baseline scenario which imposes no restrictions on the transferability of harvesting permits across vessels and collects no program administrative costs. We then consider the effects of: \( i \) a limit on the share of the total quota that can be harvested by individual vessels; \( ii \) limits on harvest permit transferability across vessel classes; and \( iii \) two forms of fee collection to pay for program administrative costs.

The results that follow assume that active IFQ-regime vessels target groundfish species only. The added costs required to switch gear types and keep abreast of the most
productive fishing sites for other species are avoided if vessels specialize in groundfish.\textsuperscript{10} Active IFQ-regime boats are assumed to harvest DTS and Non-DTS species and a small quantity of the Other species group as bycatch. Our baseline scenario assumes further that the cost of moving a vessel in and out of the PCGF is 25% of the total vessel value and that the market interest rate is 5%.

Low-cost vessels will be able to profitably bid harvest permits away from higher cost operators. For this reason, the IFQ-regime fleet will favor mid-sized vessels 60-70 feet in length. However, this conclusion ignores idiosyncratic variation in harvesting performance that is likely to be a factor in the current groundfish fleet. Any vessel that can match the cost performance of the most efficient boats in the fleet will remain active. The results that follow, which assume fleets consisting of homogeneous “representative vessels,” should be interpreted with this caveat in mind.

Table 3 reports results for three different TAC scenarios. Reported values are the means of the respective invariant distributions obtained from the solution to the dynamic fleet adjustment model (Judd 1998).

Case 1 assumes average TAC levels equal to the total landed pounds in the 2004 PacFIN data (23.25 million pounds of DTS, 21.24 million pounds of Non-DTS, and 1.46 million pounds of Other Species). In case 2 the annual TACs increase to 40.57 million pounds for DTS and 24.57 million pounds for non-DTS. Case 3 assumes annual average TACs of 40.57 million pounds for DTS and 35.53 million pounds for Non-DTS groundfish. It should be noted that the model assumes a constant ratio of DTS and non-DTS TAC levels. The effects of annual variations in the ratio of the two species groups is not captured in our model.

Our results reveal that a mix of 60- and 70-foot vessels are able to generate the highest profit levels. The model predicts an IFQ-regime fleet consisting of vessels 60 to 70 feet in length. Investigation reveals that 70-foot vessels have a higher physical capacity (1.95 million pounds per year) than that of 60-foot vessels (1.5 million pounds per year). Larger vessels have larger per-trip hold capacity and are capable of fishing in more severe weather. The static results in the previous section suggest that 70-foot boats incur higher costs per landed pound than 60-foot boats. However, 70-foot boats land more fish annually, which can provide an economic advantage particularly in a fishery with varying TACs (see Appendix for additional discussion). It follows that the relative cost efficiency of 70-foot vessels increases as the TAC% of non-DTS species increases. This explains why the number of 70-foot boats is increasing in the relative (to DTS species) TAC of non-DTS species as reported in table 3. Of course, when the TAC of all species is increased as in Case 3, the fleet size across all efficient boat classes increases.

The results suggest a switch from the current controlled access management program to IFQs could yield a significant increase in resource rents in the PCGF. For instance, our analysis finds that the 2004 groundfish catch generated zero resource rent. Instead, it could have yielded a substantial positive rent at $13.574 million (see table 3).

It is instructive to examine our results within the context of the capacity utilization literature.\textsuperscript{11} Segerson and Squires (1990) identify alternative measures of capacity for multiple-product firms. One convenient measure is the harvest level that minimizes the long-run ray average cost for a fishing vessel. The previous section (table 1) reports, for vessel length classes 60 feet and above, an estimate of this capacity measure.\textsuperscript{12} The catch

\textsuperscript{10} Based on discussion with industry members, it is reasonable to assume that there are returns to specializing in whiting and returns to specializing in groundfish species. This implies the existence of scope dis-economies in the joint harvest of whiting and groundfish species. Similar arguments hold for the harvest of shrimp and crab. These species are not harvested jointly with groundfish species and are not included under the proposed IFQ plan.

\textsuperscript{11} There is a large body of literature that examines capacity utilization in ocean fisheries. The reader is referred to Pascoe et al. (2003) and references cited therein.

\textsuperscript{12} The MES harvests for 40- and 50-foot vessels is determined as a physical capacity measure; \textit{i.e.,} the maximum amount harvested per unit of time under normal operating conditions (Johansen 1968).
per boat estimates reported in table 3 represent the per-vessel harvest levels that would be observed, on average, under an IFQ program for groundfish and a fully cost-efficient fishing fleet. For example, if TACs were maintained as in Case 1 of table 3, the model predicts vessels 60-feet in length would harvest 1.225 million pounds of groundfish per year, on average. Seventy-foot boats would harvest 1.320 million pounds of groundfish per year, on average. These estimates are optimal capacity levels under the stochastic conditions assumed in our model.

Notice that for a 60-foot boat, the optimal harvest capacity under uncertainty and costly capital adjustment is roughly 89% of the static minimum efficient harvest scale capacity (compare results in table 1 and table 3). The explanation is the following. Because it is costly to adjust the size of the groundfish fleet, the optimal (rent maximizing) fleet structure in an uncertain environment involves variation in per-vessel harvest levels and therefore deviations from the static minimum efficient harvest scale from year to year. Our model optimally balances the costs from further adjustments in the fleet size with the costs of varying the annual harvest per boat, thus increasing the average costs per harvested pound. For example, it may not be worth investing in additional capital in the event of moderately favorable but nonpermanent stock conditions. It may be preferable to increase the harvest per boat and incur a moderate increase in per-vessel average harvest costs in order to save capital adjustment costs (Singh, Weninger, and Doyle 2006).

### Table 3
Fleet Size, Harvest Cost, and Rent under IFQs

| Case 1: $\bar{Q}_{DTS} = 23.25$, $\bar{Q}_{NDTS} = 21.24$ |
|---|---|---|---|---|---|---|
| Fleet Boats | Vessel Activity Len. | Catch/Boat | Prof./Boat | % TAC Harvested DTS | Non-DTS | Permit Prices $\lambda_{DTS}$ $\lambda_{NDTS}$ Rent/Yr. |
| 28.46 | 60 | 1.225 | 0.492 | 100 | 94.3 | 0.433 | 0.264 | 13.574 |
| 7.06 | 70 | 1.320 | 0.463 | |

| Case 2: $\bar{Q}_{DTS} = 40.57$, $\bar{Q}_{NDTS} = 24.57$ |
|---|---|---|---|---|---|---|
| Fleet Boats | Vessel Activity Len. | Catch/Boat | Prof./Boat | % TAC Harvested DTS | Non-DTS | Permit Prices $\lambda_{DTS}$ $\lambda_{NDTS}$ Rent/Yr. |
| 52.05 | 60 | 1.182 | 0.478 | 99.99 | 93.0 | 0.433 | 0.264 | 20.368 |
| 2.00 | 70 | 1.274 | 0.453 | |

| Case 3: $\bar{Q}_{DTS} = 40.57$, $\bar{Q}_{NDTS} = 35.53$ |
|---|---|---|---|---|---|---|
| Fleet Boats | Vessel Activity Len. | Catch/Boat | Prof./Boat | % TAC Harvested DTS | Non-DTS | Permit Prices $\lambda_{DTS}$ $\lambda_{NDTS}$ Rent/Yr. |
| 49.24 | 60 | 1.225 | 0.481 | 100 | 94.1 | 0.434 | 0.265 | 22.408 |
| 10.81 | 70 | 1.314 | 0.458 | |

Note: Boats are annual averages. Catch/Boat and Prof./Boat is in millions of pounds and millions of $2004$, respectively. Lease prices are in $2004$. Rent/Yr. is in millions of $2004$. 
Harvest Permit Trading Restrictions

Restrictions on the concentration of quota ownership and/or restrictions on harvest permit trades across vessel classes are often incorporated into IFQ program design. These restrictions may address ancillary social objectives. However trading restrictions of any sort will reduce the rent that is generated in an IFQ-managed fishery. This section investigates the effects of two common forms of harvest permit trade restrictions, quota ownership caps, and restrictions on permit trading across vessel classes.

Quota Ownership Caps

To demonstrate the implications of quota ownership caps we simulate the equilibrium fleet structure and rent generation under a 1% limit on the total quota that is harvested by a vessel. Case 1 in table 4 shows the effect of a 1% quota share ownership cap for $Q_{DTS} = 40.57$ and $Q_{NDTS} = 24.57$. The 1% cap restricts the total pounds that can be landed by active vessels and effectively restricts the fleet size to be no less than 100 boats. The model predicts that the most preferred vessel length is now 50 feet, rather than 60- and 70-foot vessels as in the unrestricted case. Logically, 50-foot vessels have lower fixed operating costs and achieve a smaller average cost at the restricted catch levels that are implied by the 1% cap. In addition to altering the preferred vessel length, the 1% quota ownership cap results in a loss of $3.651$ million (17.9%) in annual fishery rent. This is because the fleet is maintained at an inefficiently high number of smaller boats.

Case 2 of table 4 maintains the 1% quota share ownership cap but assumes higher average TAC conditions in the fishery; $Q_{DTS} = 40.57$ and $Q_{NDTS} = 35.53$ (counterpart to Case 3 in table 3). Interestingly, the equilibrium fleet is now comprised of roughly equal mix of 50- and 60-foot boats. While tight quota caps favor smaller boats, larger average TACs leave some room for the use of cost-efficient boats and thus 60-foot boats are back in use. The quota ownership cap places an artificial limit on the annual harvest for active vessels. The model shows that this causes fluctuations in fleet size that did not occur in the unrestricted case. These unnecessary adjustments in fleet size are costly and detract from the total rent generated in the fishery. The results find that relative to the unrestricted case, annual rents decline by $3.649$ million (16.3%).

The Draft Environmental Impact Statement to Amendment 20 limits the total pounds of groundfish that can be harvested by a single vessel during each fishing season (PFMC 2008). Limits vary across individual groundfish species ranging from 2.7%–20% of the total pounds for the particular species. The regulation specifies, in addition, an aggregate groundfish (per-vessel) pound limit at 3.2% of the aggregate groundfish TAC. This regulation effectively places a lower bound on the number of active vessels at 31.25 boats. Results reported in the previous section indicate that in the absence of per-boat catch limits, the equilibrium number of vessels that make up the groundfish fleet will be above this mark. However, our model indicates that the 3.2% limit can have implications for the optimal vessel size and resource rents. Naturally a per-vessel harvest pound limit is more likely to bind for larger boats under low TACs. Simulations conducted under our smallest TAC scenario (DTS–23.25 million pounds and Non-DTS–21.24 million pounds) indicate that a 3.2% harvest limit raises the average number of 60-foot boats by 3.29 annually (to 31.75), decreases the average number of 70-foot boats by 2.7 annually (to 4.36), and reduces annual rent by about $14,000 annually.

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13 See Dinneford et al. (1999), Grafton (1996), and Committee to Review Individual Fishing Quotas (1999) for a discussion of design elements of rights-based fishery management programs.
Amendment 20 further restricts the total quota shares that can be legally controlled by a group of individuals with controlling interest. Quota ownership share limits range between 2.5%–10% depending on the groundfish species. The aggregate groundfish quota share limit (whiting excluded) is set at 2.7%.

Implications of quota share ownership restrictions may depend on the social network in the groundfish fishery. If the groundfish fleet is characterized by independent, single-boat owner/operators, a 2.7% quota share cap would translate to a lower bound of 37 separate controlling interests. Whether each interest is a single vessel owner/operator is difficult to know. If controlling interests operate multiple-vessels, ownership share constraints may bind. For example, our model predicts that a firm that operates two boats will likely have to lease quota in order to fully exploit the available economies of scale in the fishery.

Permit Trading Restrictions Across Vessel Classes

Table 5 reports the effects of a restriction on permit trading across vessel classes. For example, the Pacific halibut fishery IFQ program restricted quota share trades from smaller to larger vessel classes (trading in the opposite direction; i.e., from larger to smaller vessel classes was permitted).

The results in table 5 are not surprising. In particular if 50% of the TAC must be harvested by 50-foot boats, 65 such boats are active in the fleet. The optimal number of 60-foot vessels falls from 49.24 (see Case 2 in table 3) to 14.59. Overall, the trading restriction reduces the rent in the fishery by $2.120 million per year (9.46%). The results for Case 2, which allocate 50% of now a larger TAC to 50-foot boats, increase the number of these vessels even further and cause further reductions in the fishery rent.

\[ Q_{DTS} = 40.57, \quad Q_{NDTS} = 24.57 \text{ with 1\% Quota Ownership Cap} \]

<table>
<thead>
<tr>
<th>Fleet</th>
<th>Vessel Activity</th>
<th>% TAC Harvested</th>
<th>Rent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boats</td>
<td>Len.</td>
<td>Catch/Boat</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>0.645</td>
<td>0.262</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fleet</th>
<th>Vessel Activity</th>
<th>% TAC Harvested</th>
<th>Rent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boats</td>
<td>Len.</td>
<td>Catch/Boat</td>
</tr>
<tr>
<td>49.53</td>
<td>50</td>
<td>0.708</td>
<td>0.308</td>
</tr>
<tr>
<td>50.46</td>
<td>60</td>
<td>0.776</td>
<td>0.277</td>
</tr>
</tbody>
</table>

Note: Boats are annual averages. Catch/Boat and Prof./Boat is in millions of pounds and millions of $2004, respectively. Lease prices are in $2004. Rent/Yr. is in millions of $2004.

The Amendment states (page 15): “Quota share controlled by a person shall include those registered to that person, plus those controlled by other entities in which the person has a direct or indirect ownership interest, as well as shares that the person controls through other means.”
Here we examine the impact of landing fees collected to support an on-board observer program. While about 25% of groundfish trawl trips had observers during 2004, observer coverage will be mandatory on all trips under the proposed IFQ program. This is because quota is designated for the vessel catch rather than landings, thus making it necessary to measure the catch on trawl trips. We first consider a fee that is levied equally on all boats on a per-day (at sea) basis. It is assumed that the cost per observer is $350 per day.

The results that follow are based on an estimate of how many days per year a boat will be at sea when employed to its full physical capacity:

<table>
<thead>
<tr>
<th>Length (feet)</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Capacity Days at Sea</td>
<td>100</td>
<td>130</td>
<td>150</td>
<td>160</td>
<td>170</td>
<td>170</td>
</tr>
</tbody>
</table>

Based on the above estimates, table 6 shows the effects of a $350 per day fee on fleet structure, vessel harvest levels, and rent generation.

A uniform per-day fee on all vessels tilts the optimal fleet size towards bigger boats, simply because the cost per-pound increase from adding the observed charge is smaller. As is evident, while in the no-fee case the average fleet size of 60-foot and 70-foot vessels are about 52 and 2, respectively, with the daily observer charge the average number of 60-foot and 70-foot boats is 28 and 22, respectively. Also notice that not only are a higher number of 70-foot vessels hired, but their mean catch levels also rise, while the catch of 60-foot vessels declines. As a result, the profitability (net of observer costs) of 70-foot vessel increases considerably, whereas the profit of 60-foot boats falls.

Table 5
Permit Trading Restrictions across Vessel Classes

<table>
<thead>
<tr>
<th>Fleet Boats</th>
<th>Vessel Activity</th>
<th>% TAC Harvested</th>
<th>Rent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Catch/Boat</td>
<td>DTS</td>
<td>Non-DTS</td>
</tr>
<tr>
<td>65</td>
<td>50</td>
<td>0.745</td>
<td>0.324</td>
</tr>
<tr>
<td>14.59</td>
<td>60</td>
<td>1.016</td>
<td>0.334</td>
</tr>
</tbody>
</table>

Case 2: $Q_{DTS} = 40.57, Q_{NDTS} = 35.53, 50\% \text{ of Quota Allocated to 50-foot Boats}$

<table>
<thead>
<tr>
<th>Fleet Boats</th>
<th>Vessel Activity</th>
<th>% TAC Harvested</th>
<th>Rent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Catch/Boat</td>
<td>DTS</td>
<td>Non-DTS</td>
</tr>
<tr>
<td>75</td>
<td>50</td>
<td>0.746</td>
<td>0.310</td>
</tr>
<tr>
<td>17.5</td>
<td>60</td>
<td>1.013</td>
<td>0.315</td>
</tr>
</tbody>
</table>

Note: Boats are annual averages. Catch/Boat and Prof./Boat is in millions of pounds and millions of $2004, respectively. Lease prices are in $2004. Rent/Yr. is in millions of $2004.

Observer Costs, Landing Fees, and Optimal Fleet Size

Here we examine the impact of landing fees collected to support an on-board observer program. While about 25% of groundfish trawl trips had observers during 2004, observer coverage will be mandatory on all trips under the proposed IFQ program. This is because quota is designated for the vessel catch rather than landings, thus making it necessary to measure the catch on trawl trips. We first consider a fee that is levied equally on all boats on a per-day (at sea) basis. It is assumed that the cost per observer is $350 per day. The results that follow are based on an estimate of how many days per year a boat will be at sea when employed to its full physical capacity.

<table>
<thead>
<tr>
<th>Length (feet)</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Capacity Days at Sea</td>
<td>100</td>
<td>130</td>
<td>150</td>
<td>160</td>
<td>170</td>
<td>170</td>
</tr>
</tbody>
</table>

Based on the above estimates, table 6 shows the effects of a $350 per day fee on fleet structure, vessel harvest levels, and rent generation.

A uniform per-day fee on all vessels tilts the optimal fleet size towards bigger boats, simply because the cost per-pound increase from adding the observed charge is smaller. As is evident, while in the no-fee case the average fleet size of 60-foot and 70-foot vessels are about 52 and 2, respectively, with the daily observer charge the average number of 60-foot and 70-foot boats is 28 and 22, respectively. Also notice that not only are a higher number of 70-foot vessels hired, but their mean catch levels also rise, while the catch of 60-foot vessels declines. As a result, the profitability (net of observer costs) of 70-foot vessel increases considerably, whereas the profit of 60-foot boats falls.

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15 Estimates of daily observer costs were provided by Merrick Burden (Pacific Fisheries Management Council staff) and Jonathan Cusiak (manager of the observer program at the Northwest Fisheries Science Center).
Table 6
Implications of Landing Taxes to Fund Observers

| Case 1: No Charge for Observers | | | |
|---------------------------------|--|--|--|--| |--|--|--|--| |--|--|--|--|
| **Boats** | **Fleet** | **Vessel Activity** | **Rent** | **Rent/Yr.** |
| **Boats** | **Len.** | **Catch/Boat** | **Prof./Boat** | **Rent** | **Rent/Yr.** |
| 345.05 | 60 | 1.182 | 0.478 | 20.368 | 2.00 | 70 | 1.274 | 0.453 |
| 2.00 | 70 | 1.274 | 0.453 | | |

| Case 2: $350/Day Observer Charge | | | | |
|---------------------------------|--|--|--|--| |--|--|--|--| |--|--|--|--|
| **Boats** | **Fleet** | **Vessel Activity** | **Obs. Cost/Boat** | **Rent** | **Rent Loss** | **Obs. Fees** |
| **Boats** | **Len.** | **Catch/Boat** | **Prof./Boat** | **Rent** | **Loss** | **Fees** |
| 27.44 | 60 | 1.087 | 0.506 | 0.038 | 2.170 | 2.231 |
| 21.81 | 70 | 1.585 | 0.540 | 0.046 | | |

Note: TACs are set at $DTSQ = 40.57$ and $NDTSQ = 24.57$. Boats are annual averages. Catch/Boat and Prof./Boat is in millions of pounds and millions of $2004$, respectively. Lease prices are in $2004$. Rent/Yr. is in millions of $2004$.

Table 7 shows that the percentage TAC harvested is almost unaffected by the per-day observer charge. Clearly, as a part of the rent must go towards paying for observers, the lease prices of both species is now smaller. However, the lease price of non-DTS species drops less, since fees favor higher catch boats which are relatively more efficient in harvesting non-DTS species.

Table 7
Implications of Landing Taxes to Fund Observers

| Case 1: No Observer Fee | | | |
|-------------------------|--|--|--|--| |--|--|--|--| |--|--|--|--|
| % TAC Harvested | Permit Prices | |
| **DTS** | **Non-DTS** | $\lambda_{DTS}$ | $\lambda_{NDTS}$ | |
| 99.99 | 93.30 | 0.433 | 0.264 |

| Case 2: With $350/Day Observer Fee | | | |
|----------------------------------|--|--|--|--| |--|--|--|--| |--|--|--|--|
| % TAC Harvested | Permit Prices | |
| **DTS** | **Non-DTS** | $\lambda_{DTS}$ | $\lambda_{NDTS}$ | |
| 100.00 | 94.11 | 0.417 | 0.257 |

Note: TACs are set at $DTSQ = 40.57$ and $NDTSQ = 24.57$. Lease prices are in $2004$.

The rent reduction of $2.170 million (10.65%) is due to the payments to observers and changes in production. The mean of total observer payments are calculated to be $2.234 million, and therefore the changes in production due to distortions amounts to $0.064 million per year. Note that our model does not consider any benefits provided by the observers (such as improved data on total catch for stock assessment); calculated
losses are likely to be smaller or even turn into net benefits if the benefits provided by the observers are taken into account.

We next consider alternative ways to raise funds for supporting an observer program. The first is a per-pound landings fee of $0.033, while the second is an ad-valorem landing set at 7% of the dockside price (table 8). These rates generate total fees roughly equal to those obtained under the per-boat observer fee considered above (table 6).

The two fee-collection schemes yield almost identical outcomes in terms of their effect on fleet structure. Relative to a per-day observer charge, the boats employed now are closer to the no-fee scenario (see table 6). However, fees still favor larger vessels. Why? Notice that 60-foot vessels operate relatively closer to capacity in comparison with larger vessels. Since fees are based on harvest quantities, the relative benefits of 60-foot vessels decreases.

It is also worth noting that while the %TAC harvest of DTS species is unchanged relative to the no-fee case (as well under per-day fee), the %TAC harvest of non-DTS species declines by almost 2.5% (1.3%) under an ad-valorem fee. The reason is simple. A landing fee of $0.0325 per pound decreases the effective price of DTS species by about 6.5%, whereas for non-DTS species the decline is about 11%. Ad-valorem fees affect all effective prices in the same proportion. However, to the extent that the TAC of non-DTS species was not being harvested fully even with no-fees, a lower effective price depresses its harvest even further.

<table>
<thead>
<tr>
<th>Case 1: With $0.033/lb. Landing Fee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Boats</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>42.86</td>
</tr>
<tr>
<td>7.67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case 2: With 7% Dockside Price Landing Fee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Boats</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>42.35</td>
</tr>
<tr>
<td>8.89</td>
</tr>
</tbody>
</table>

Note: TACs are set at $\tilde{\theta}_{\text{DTS}} = 40.57$ and $\tilde{\theta}_{\text{NDTS}} = 24.57$. Boats are annual averages. Catch/Boat and Prof./Boat is in millions of pounds and millions of $2004, respectively. Lease prices are in $2004. Rent/Yr. is in millions of $2004.

Conclusions

This article examines the economic implications of adopting an IFQ management program for Pacific Coast limited entry trawl non-whiting groundfish. An important focus of our analysis is the implications of the IFQ program design on the composition of the fishing fleet and the resource rents that are generated in the fishery. The conceptual approach follows recent work by Weninger and Waters (2003) and Singh, Weninger, and Doyle (2006). We first estimate cost inefficiency in 2003–04 cost data collected from groundfish vessels under the controlled access program. Vessel-level costs are then incorporated into a dynamic optimizing framework to study equilibrium fleet structure and composition under an IFQ program. We then make alternative policy predictions.
Our results suggest that the trawl groundfish fleet, which consisted of 117 vessels during 2004–05 under controlled access, will be reduced by roughly 50–66% to 40–60 vessels under an IFQ program. This reduction in the fleet size will result in cost savings in the range of $18–$22 million annually (all values are in terms of base year 2004). The results predict that smaller and larger vessels will exit, leaving mid-sized vessels (60- to 70-feet in length) to carry out the bulk of the harvesting activities. The vessels that remain active will, on average, be more cost efficient and will benefit from economies of scale that are currently unexploited in the fishery. The cost savings estimates are significant, amounting to roughly 60% of costs incurred currently. The results suggest IFQ management may be an attractive option for the PCGF.

However, if the IFQ program design places additional restrictions on permit trading, such as caps on vessel level harvests or restrictions on permit trading across vessel classes, the cost savings will be smaller. In general, tight harvest quota ownership caps for individual vessels will favor smaller boats. Restrictions on permit trading across vessel classes will keep vessels active that would otherwise exit the fishery. Both forms of trading restrictions will reduce rents that are generated under the IFQ program.

We have also examined the implications of funding observers through “days-at-sea” and landing taxes for the optimal fleet size as well as harvest outputs. In general, both taxes favor larger vessels. While days-at-sea fees only distort the optimal mix of the active fleet, landing taxes by affecting relative dockside prices, distort both the fleet structure and harvest quantities. As a result, net of tax revenues, losses under landing taxes are higher. This suggests that funding observers through a days-at-sea fee is relatively more efficient. To the extent that such fees favor larger boats, a progressive capacity-based, days-at-sea fee may perform even better. Further work to identify rent collection schemes that can address specific management objectives should prove useful (Grafton 1992, 1994).

Overall, our results show that the specific design elements in IFQ fisheries management program can have important implications for the nature and extent of fleet restructuring. We find that commonly used design elements, such as quota trading restrictions and rent collection, to pay for administrative costs will favor certain capital types, and will therefore have redistributive implications during transition to a rights-based management program. Insights drawn from our analysis provide guidance for regulators concerned with the distributional and efficiency impacts of fisheries management reform.

Our analysis has focused on estimating changes in fleet structure and cost savings when controlled access regulation is replaced with IFQs. Additional impacts, such as changes in product quality, safety conditions, discarding, and costs of management, may also be important (Branch, Rutherford, and Hilborn 2006; Casey et al. 1995; Committee to Review Individual Fishing Quotas 1999). An analysis of these impacts is reserved for future work.

Lastly, additional challenges (e.g., determining which species are included in the IFQ program or the extent of the observer coverage) may be encountered in the design of IFQ management for Pacific Coast groundfish (Squires et al. 1998; Grafton, Nelson, and Turris 2005). Our estimates reveal that substantial rent gains are available if these challenges can be addressed.

References


Appendix: Data and Cost Function Estimation

This appendix describes the data and the econometric methods used to estimate harvesting costs and inefficiency under the controlled access management program in the PCGF.

Data

A survey of fishing expenses for the limited entry trawl fleet during 2003 and 2004 was conducted by the National Marine Fisheries Service in cooperation with the Pacific States Marine Fisheries Commission. Data collected includes: i) annual expenses for captain, crew, fuel, ice, bait, provisions, and vessel repair and maintenance; ii) revenue sources other than landings on the Pacific Coast (which are available through PacFIN); iii) physical characteristics of the vessel such as length, engine horsepower, fuel capacity, and fuel consumption; iv) how frequently the vessel owner serves as captain of the vessel; and v) the share system used to remunerate the captain and crew. By combining survey data with data available on Pacific Coast landings through PacFIN, it is possible to get a complete picture of revenues and costs for each vessel.

Survey responses were received from 111 of the 151 vessels active in the limited entry trawl component of the PCGF during 2004. Two factors prevented the use of data from some survey respondents in this study. First, some survey respondents failed to
provide expenditure data for key cost categories or provided unreasonable data. Second, some vessels landed a large component of their annual catch in Alaskan waters. Available data did not allow us to separate the reported costs into Pacific Coast expenditures and expenditures incurred in Alaskan waters. Removal of vessels with missing cost data, unreasonable cost data, or a significant portion of their revenue from Alaskan waters reduced the number of observations to 62 in 2003 and 68 in 2004.

Fixed Costs

Fixed costs incurred by vessel owners include: (i) expenditures on gear and vessel repairs, maintenance, and improvements; (ii) the rental price of vessel capital; and (iii) payments to the vessel captain. We assume that skilled captain labor cannot be costlessly moved in and out of the groundfish fishery. Captain labor is therefore included as a component of the capital endowment and subject to costly seasonal adjustment.  

We require estimates of the fixed cost components for different capital types. Our data contain complete information on vessel lengths and fuel capacity. Therefore, we use these two characteristics as proxies for the capital embodied in our vessel operations. Alternative functional forms (linear, quadratic, cubic, log-log, etc.) that map cost components of observable vessel characteristics were investigated. We report results from functional forms that were parsimonious and provided a reasonable fit to the data.

Survey respondents provided expenditures as well as explanations for gear and vessel repairs, maintenance, and improvements. Hereafter, this expense category will be denoted \( mr \) (maintenance and repair). Reported \( mr \) expenses varied widely across vessels due to the fact that some vessel owners made expensive engine repairs or replaced engine or drive train parts. It is clear from the data that these types of repairs are incurred only occasionally.

We estimate the following simple model to obtain an expected value for the \( mr \) expense category:

\[
\ln(mr) = -6.616 + 0.069 \times len - 2.87e^{-4} \times len^2 + 3.5e^{-5} \times fuel\_cap, \\
(0.654) \quad (0.016) \quad (1.03e^{-4}) \quad (0.8e^{-5})
\]

where \( len \) is length and \( fuel\_cap \) is fuel capacity of vessel \( i \). Ordinary least squares is used to estimate the above model using reported costs from 91 vessels with complete data over two seasons, for a total of 182 observations. Estimated parameters have low standard errors (reported in parentheses), and each is statistically different from zero at the 99% level of confidence. The adjusted R-square for the model is 0.481, reflecting the considerable variation in this expense category.

A second component of annual fixed cost is the rental price of the vessel capital. Our data include survey respondents’ self-assessments of the sale value of their vessel (45 observations). To smooth idiosyncratic differences in reported values, which we denote \( p_{ij} \), we conduct a least squares regression to obtain the following equation:

\[\text{16} \text{ Active vessels under the IFQ program are assumed to harvest groundfish year round in order to exploit all available economies of scale. The assumption that captain labor services are non-malleable is therefore reasonable for the scenario that we consider.} \]

\[\text{17} \text{ We note that other proxies for capital, such as vessel gross registered tonnage, hull construction, engine type, and electronic equipment were unavailable for additional discussion of measurements of fishing capital) (see FAO (1999). We have no reason to believe that the proxies and functional relationships that we specify will bias our calibration of harvesting costs in any way.} \]

\[\text{18} \text{ A dummy variable for 2004 was included in an earlier regression but found to have no significant effect on maintenance and repair costs.} \]
\[ p_k = 0.931 - 0.032 \times \text{len} + 3.16 \times 10^{-4} \times \text{len}^2 + 1.3 \times 10^{-5} \times \text{fuel\_cap} + 8.4 \times 10^{-5} \times D_{\text{len}>100} \]

\[(0.595) \quad (0.018) \quad (1.25 \times 10^{-4}) \quad (1.0 \times 10^{-5}) \quad (4.4 \times 10^{-5}). \quad (7)\]

The parameter estimates in equation (7) also have low standard errors (each parameter is statistically different from zero at the 99% levels of confidence). The adjusted R-square for the model in equation (7) is 0.935.

Among survey respondents, slightly over 80% of trips targeting groundfish are made with the vessel owner serving as captain. Examination of the survey data revealed that the reported skipper wage paid to the owner/operators of a vessel; i.e., the wage that the owner paid himself was, in some cases, a token payment that did not reflect a true market wage. These token payments are not comparable to the wage paid to hired skippers. This data anomaly is caused by individuals who serve as both the vessel owner and vessel captain, choosing to take their compensation as residual vessel profits. To reduce the effect of this data anomaly on the analysis, we assume the vessel captain is paid the median wage in our data, which is $80,000 annually.

Combining the above results yields an annual fixed cost estimate for the groundfish vessels in our data:

\[ fc_k = \text{cap\_wage} + m r + \rho p_k \quad (8)\]

where \( \text{cap\_wage} \) is the captain wage and \( m r \) and \( p_k \) are the fitted values obtained from the above regression models (recall that \( \rho \) is an annual interest rate).

Variable Operating Costs

Industry sources indicate that trip-level landings are influenced largely by the demand for fish from groundfish processors. It is therefore reasonable to assume that the objective of vessel owner/operators is to minimize the costs of landing the groundfish quantities demanded by processors. We assume further groundfish harvest costs are influenced by the skill level of the vessel skipper and randomness associated with fishing in an uncertain marine environment. Stochastic frontier econometric methods are well suited for estimating harvesting costs under these assumptions. A summary of the stochastic frontier model is available in Kumbhakar and Knox Lovell (2000). Our econometric specification closely follows Hadri (1999).

Empirical tractability requires that fish species be aggregated into output groups. Industry participants and managers were consulted to identify species that are harvested using similar gear, at similar depth, and in similar geographical regions.\(^{19}\) It was determined that six output groupings provide a reasonable balance between model tractability and potential inaccuracy resulting from aggregation. Our species groups include: i) whiting; ii) DTS groundfish species (Dover sole, thornyheads, and sablefish); iii) non-DTS groundfish species, which include all groundfish species not included in the whiting and DTS groups; iv) crab; v) shrimp; and vi) other, which includes salmon, halibut, highly migratory, and pelagic species. Harvested quantities within each output category are aggregated linearly. The aggregation procedure assumes that optimal input choices required to harvest these output groups can be chosen independently of the mix of species within each group or alternatively that the harvest technology exhibits weak output separability. Linear aggregation implies a constant rate of product transformation among species that make up each output group.

\(^{19}\) There are over 82 separate species of groundfish listed in the Fisheries Management Plan.
We proceed under the maintained hypothesis that the trawl harvest technology is joint-in-inputs (Lau 1978; Squires 1987a,b for additional discussion of joint-in-inputs technologies). First and foremost, the factor services that are provided from a fishing vessel and its crew during a particular calendar period must be viewed as a fixed but allocatable input (Shumway, Pope, and Nash 1984). We are further convinced that single species production and cost functions do not exist in our empirical setting due to the non-selectivity of the trawl gear; i.e., groundfish fishermen may have considerable latitude to alter the mix of species that is intercepted with their gear, but they cannot costlessly specialize in the harvest of single groundfish species (Branch and Hilborn 2008).

Table 9 reports descriptive statistics from 2001-2006. The fleet is divided into Whiting and non-Whiting or *Groundfish* vessels.20 Whiting is harvested with mid-water trawls as opposed to bottom trawls which are used to harvest most other groundfish species. Vessels targeting whiting tend to be larger and harvest considerably more pounds per trip and per year than do vessels targeting groundfish species. Moreover, fishermen indicate that they are able to target whiting almost exclusively. PacFIN data supports this claim. We find the share of whiting landings for vessels that target whiting is often in excess of 0.90 and, in some cases, as high as 0.99. Catch patterns in the data are consistent with feedback from industry that consider whiting boats a separate segment of the groundfish fleet. Comparing trips and landings per vessel per year in table 9 highlights the differences between whiting and groundfish vessels. In particular, the average and maximum landings in pounds for whiting vessels is an order of magnitude larger than for non-whiting groundfish vessels.

Table 9 reveals further information about the structure of the groundfish fleet under the current management regime. First note that the number of vessels reporting landings dropped markedly in 2004. The cause of this decline was a government- and industry-sponsored vessel buyback program which permanently retired 91 trawl limited-entry permits.21 The effect of the buyback, which reduced the number of limited entry permits from 274 to 183, is evident in table 9. The mean number of trips taken and the harvest per vessel declined during 2001-2003 prior to the buyback (this may explain why the buyback program was supported by managers and industry) and increased during the post buyback period, 2004-2006.

A final noteworthy aspect in table 9 is the variation in the trips per year and the annual harvest among active vessels. For example, the maximum harvest quantity in many years is 3-5 times larger than the per-vessel average. The standard deviation of trips and landings is also high, indicating considerable variation in landed pounds. Some of this variation is explained by differences in vessel sizes and mix of target species. A second explanation, however, is variation in vessel capacity utilization, which is common in fisheries managed under limited-entry programs (Weninger and Waters 2003; Singh, Weninger, and Doyle 2006).

Variable operating costs for a representative vessel in our sample (as above we avoid vessel subscripts to ease notation) are assumed to follow:

\[
\ln c_k = \beta_0 + \sum \beta_m q_m + \beta_w \ln w_t + \beta_k k + \beta_z z + \beta_x x_t + \nu + \epsilon, \tag{9}
\]

where \(q_m\) is an \(m\)-vector of landed quantities, \(w_t\) is the fuel price in year \(t\), \(k\) is a measure of vessel capital, and \(z\) denotes other exogenous factors that may impact variable harvesting costs. The fuel price is entered logarithmically to accommodate the input-price concavity property of the cost function. The unknown parameters are \(\{\beta_0, \beta_m, \beta_w, \beta_k, \beta_z, \beta_x\}\).

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20 Whiting vessels are delineated as those harvesting less than 100,000 pounds of groundfish species annually.

Following the stochastic frontier literature, we append an additive composed error term to the right-hand side of equation 9.

### Table 9
Whiting and Groundfish Fleet Catch Statistics: 2001-06

<table>
<thead>
<tr>
<th>Year</th>
<th>Whiting Boats</th>
<th>Groundfish (non-whiting) Boats</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>28</td>
<td>45.6</td>
</tr>
<tr>
<td>2002</td>
<td>28</td>
<td>33.9</td>
</tr>
<tr>
<td>2003</td>
<td>32</td>
<td>34.1</td>
</tr>
<tr>
<td>2004</td>
<td>26</td>
<td>52.6</td>
</tr>
<tr>
<td>2005</td>
<td>29</td>
<td>48.0</td>
</tr>
<tr>
<td>2006</td>
<td>34</td>
<td>41.7</td>
</tr>
</tbody>
</table>

Note: Ave., Std., and Max. denote average, standard deviation, and maximum values, respectively. Whiting boats land more than 100,000 pounds of whiting per year. Harvest quantities are thousands of pounds.

We use two proxies for vessel capital; vessel length and fuel capacity. The fuel capacity variable is included as a proxy for the power of the vessel’s engine and an indication of the size of net that can be dragged through the water and the quantity of fish that can be winched to the vessel deck and hauled back to port.

The components of $z$ include the proportion of time that the vessel owner serves as captain and the latitude of the vessel’s home port. The ownership variable may capture differences in productivity that result from ownership structure. For example, hired skippers tend to be full-time fishermen who, due to the fact that they spend more time at sea, may develop better knowledge about the location of high concentrations of groundfish. The latitude variable is included as a proxy for possible differences in stock abundance across geographical regions or differences in average steaming time from port to the fishing ground. It should be noted, however, that vessels are mobile; if certain regions of the fishery are more productive than others and information about abundance flowed freely among fishermen, vessels would likely relocate to more productive regions. The inclusion of the latitude measure may, however, capture short-run or out-of-equilibrium differences in regional productivity.

Data on abundance of all groundfish species stocks are unavailable. To capture unobserved stock effects, we replace $\beta$ with $\beta_{2004}$ and interact this parameter with a dummy variable that is set to unity in 2004 and zero otherwise. Limitations of missing stock data are discussed below.
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Heteroskedasticity (which is common in panel data) can bias the analysis of inefficiency in stochastic frontier models (Caudill, Ford, and Gropper 1995). Heteroskedasticity may be particularly prevalent in commercial fishing data. Table 9, in particular, reveals considerable variation in the number of annual fishing trips taken in the groundfishery. If one postulates that the catch on each trip is partly random due to unforeseen weather conditions and/or stock abundance, the law of large numbers would suggest that the variance of the two-sided error, $\sigma^2$, will be larger for vessels taking fewer trips. Heteroskedasticity in the asymmetric error component may also be important. For example, some vessels may target a different mix of species from year to year which could impact the ability of the skipper to consistently locate targeted fish. The doubly-heteroskedastic cost frontier framework of Hadri (1999) is adopted to capture these elements.

The symmetric error is denoted $\epsilon$ and is assumed to be independently normally distributed with zero mean and finite variance; $\epsilon \sim N(0, \sigma_\epsilon^2)$. The asymmetric error term $\nu$ captures the cost inefficiency of harvesting operations. We assume that $\nu$ is distributed as a half-normal random variable with variance $\sigma_v^2$. We assume $\sigma_\epsilon = \exp(\theta_0 + \theta_1 \text{trips})$, where trips is the number of trips taken during the fishing year. Similarly, we assume $\sigma_v = \exp(\gamma_0 + \gamma_1 \text{div})$, where div is a measure of diversification in the species mix. We compute div as the sum of squared landing shares. Thus a vessel that specializes in the harvest of one output group only would have $\text{div} = 1$, whereas vessels that target a mix of output groups would have a lower value for this variable.

Parameter estimates are reported table 10. The parameters associated with harvest of the six species groups $\beta_1$ through $\beta_6$ are positive, and with the exception of the other-species group parameter $\beta_6$, are statistically different from zero at or above the 95% confidence level. The marginal harvesting costs are calculated as $\partial c / \partial q_i = c \beta_i$. Marginal cost estimates are consistent with information provided by industry and average dockside prices in the fishery. The marginal cost per pound of whiting, which is the highest volume species, is lowest at $0.012$ (the average dockside price for whiting obtained from the PacFIN data base is $0.046$). Marginal costs for the deeper water DTS group is $0.154$ (average dockside price is $0.523$). The marginal cost for the non-DTS species group, which is harvested from shallower waters, is estimated at $0.069$ (average dockside price is $0.305$). Our results find that the marginal cost for crab which, based on feedback from industry, is a more labor intensive fishing activity, is $0.358$ (average dockside price is $0.624$). Lastly, the marginal cost for the Other species group is estimated at $0.230$, with average dockside price of $1.085$.

The parameter associated with the fuel price variable, $\beta_w$, is negative with a p-value of 0.072. If this result is not a type II statistical error, it implies that the conditional output (Hicksian) demand for fuel is increasing in the price of fuel, which violates our maintained hypothesis of cost minimizing behavior. There are alternative explanations for the perverse sign, the most likely being the assumptions that underlie the construction of our fuel price variable. Data limitations require that an annual average fuel price be used whereas fuel prices and consumption vary seasonally. During 2003-04, fuel prices increased gradually over the winter of 2003-04 before increasing dramatically in May 2004. Second, our data report the home port of the groundfish vessel but do not indicate where and when the vessel operator purchases fuel. Vessels do not always fish near their home port and fuel prices vary along the West Coast, making it difficult to infer fuel prices actually paid by individual vessel operators. A third factor is that despite the rise in fuel prices that began in May 2004, the annual average prices differed by less than $0.05$ in 2003 and 2004. The small variation in fuel prices makes identification of the fuel price effect difficult. Lastly, fuel prices across regions are correlated with our latitude variable.

22 A Tornqvist index is used to calculate the price of multiple species output groups. We then calculate the average price index across vessels that reported positive landings.
The simple correlation between fuel price and latitude is $-0.78$. These considerations suggest that the perverse sign indicated for $\beta_w$ does not warrant a reconsideration of the cost-minimizing behavioral hypothesis.

The results indicate that the latitude variable has a negative impact on variable costs but that the effect is not significantly different from zero. As noted above, our data do not indicate the location of fishing, which complicates the identification of regional effects if they do indeed exist. If vessels fish adjacent to their home port year round, we can conclude from our results that there are no significant differences in variable costs across geographical regions in the groundfish fishery.

The results suggest hired skippers incur lower variable costs than owner-skippered vessels. One explanation for this result is that hired skippers fish more and have better information about the location of high concentrations of groundfish. Our data indicate that vessels with hired skippers harvest almost four times more fish per year than owner/skipper boats.

The parameter associated with the 2004 dummy variable is negative and statistically different from zero at the 99% confidence level, indicating that variable costs declined between 2003 and 2004. Several factors could cause this finding. First, any factor (biological or economic) that changed between 2003 and 2004 and is not accounted for in

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As a further check for multicolinearity we regressed the fuel price variable on a constant term, the latitude variable, and the 2004 dummy variable. This regression yielded an R-square statistic of 0.65.

This conclusion does not suggest that abundance is homogenous in the fishery, but that after controlling for proximity of the fishing grounds from port, weather, etc., we find no identifiable differences in costs per landed pound of fish across port latitude.
the econometric model will influence the estimate of $\beta_{2004}$. One such factor may be the permit buyback program, which likely retired higher-cost vessels from the groundfish fleet. Another cause could be increased stock abundance in 2004. Independent estimates indicate that the stock levels for some key groundfish species (Dover and petrale sole) did increase between 2003 and 2004 (Lai et al. 2004; Stewart 2005). Without a comprehensive account of abundance for all groundfish species, however, the true cause of the 2004 cost decline cannot be determined.

Turning to the heteroskedasticity terms, the results indicate $\sigma^2\varepsilon$ is a declining function of the number of trips taken per year. This relationship is as expected. We find no statistically significant heteroskedasticity in the variance of the asymmetric error term, $\sigma^2_v$.

Estimate Costs

Table 11 reports results for six vessel length classes: 40, 50, 60, 70, 80 and 90-foot boats. Column 1 in table 11 reports the number of sample boats falling into each length class window. We determine fuel carrying capacity for a vessel of length $L$ as the average fuel capacity for vessels of similar length. For example, a 50-foot vessel is assumed to be able to carry 2,587.6 gallons of fuel. This value is determined as the average fuel capacity for the 21 sample vessels with lengths ranging between 45 and 55 feet in length (estimates for the remaining length classes were obtained similarly).

Column 4 of table 11 reports estimates of the maximum annual pounds (a measure of physical harvesting capacity) for each vessel class. These estimates are obtained by examining the maximum landed pounds reported by each vessel category during 2003 and 2004, historical maximum landings by vessel class, and consultation with groundfish fishermen. A problem we face is that recent harvest activity has been generated under bi-monthly landings restrictions imposed under the Limited Entry management program. By design, these regulations restrict per-vessel harvest, which suggests that the annual landings reported in table 2 will be low compared to the total landings under IFQs; i.e., when bi-monthly catch limits are eliminated. Historical data generated before bimonthly limits could indicate the landings capacity under IFQ management. However, historical data will be conditional on stock conditions that prevailed in the fishery in past years. To circumvent this problem we consulted groundfish fishermen and all available data to settle on the capacity estimates reported in table 11. The sensitivity of the results to capacity constraint estimates is examined further below.

Vessel value and maintenance and repair expenditures estimates (equations (7) and (6) above) are reported in columns 5 and 6, respectively. Notice that estimates of Vessel Value indicate that 40-foot boats sell for $188,634, whereas 50-foot boats sell for $177,984. One would expect the relationship between vessel length and value to be monotonic. The violation of this relationship for 40-foot boats is likely due to estimation error caused by a low number of observations on smaller vessels. It should also be noted that the cost data include only four observations for vessels in excess of 85 feet in length. The results for the smallest and largest representative vessel classes should be viewed with this limitation in mind.

For each vessel length class we calculate the harvest quantity that minimizes ray average cost (RAC). Note that RAC depends on the mix of harvested species. PacFIN data indicate that the 2004 Limited Entry fleet harvested 197.691 million pounds of whiting, 23.246 million pounds of DTS species, 21.238 million pounds of non-DTS species, 8.018 million pounds of crab, 5.112 million pounds of shrimp, and 1.457 million pounds of other species. Given our focus on non-whiting boats, we posit a target harvest vector that includes no whiting but positive quantities of the remaining five species groups, where the mix is set equal to the fleet-wide mix for these species.
A final required assumption is the level of cost efficiency attained by representative vessels. To investigate the role of inefficiency, we calculate the minimum efficient scale of production and corresponding RAC for the 25%, 50%, and 75% percentile values estimated from our sample.

Table 12 reports the catch per vessel (total pounds of all species) and minimum RAC attained for efficiency levels $\exp(v) = 1.164$, $1.215$, and $1.264$. As asterisk associated with the catch-per-vessel estimate indicates that the vessel’s physical harvesting capacity constraint binds.

The results in table 12 show that the variation in cost efficiency has only small effects on the scale-efficient catch per vessel and RAC. Higher inefficiency lowers total catch and raises RAC as required. Comparing vessel lengths, the results indicate that RAC is lowest for 50-foot vessels, although the difference between 50- and 60-foot vessels is small. Results indicate that smaller (40-foot) vessels and larger (70-90 foot) vessels incur higher costs per harvested pound. The finding that larger vessels incur higher costs must be interpreted cautiously, as the analysis in this section is static and does not consider value of harvesting flexibility offered by larger boats, which is important in an uncertain fishing environment.

### Table 11
Representative Vessel Costs and Characteristics

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Length</th>
<th>Fuel Cap.</th>
<th>Catch Cap.</th>
<th>Vessel Value ($)</th>
<th>Main./Repair ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>&lt;45</td>
<td>1,000.0</td>
<td>500,000</td>
<td>188,634</td>
<td>93,920</td>
</tr>
<tr>
<td>21</td>
<td>50</td>
<td>2,587.6</td>
<td>850,000</td>
<td>177,984</td>
<td>102,695</td>
</tr>
<tr>
<td>28</td>
<td>60</td>
<td>4,576.8</td>
<td>1,500,000</td>
<td>235,675</td>
<td>115,435</td>
</tr>
<tr>
<td>28</td>
<td>70</td>
<td>6,964.3</td>
<td>1,950,000</td>
<td>361,665</td>
<td>132,977</td>
</tr>
<tr>
<td>19</td>
<td>80</td>
<td>10,631.6</td>
<td>2,250,000</td>
<td>567,044</td>
<td>158,210</td>
</tr>
<tr>
<td>4</td>
<td>85*</td>
<td>11,500.0</td>
<td>2,250,000</td>
<td>800,507</td>
<td>178,878</td>
</tr>
</tbody>
</table>

Note: Fuel Cap. denotes vessel fuel capacity in gallons; Catch Cap. denotes annual harvesting capacity in pounds; Main./Repair denotes annual maintenance and repair expenditures.

### Table 12
IFQ-Regime Harvest Levels and Ray Average Cost Estimates

<table>
<thead>
<tr>
<th>Length</th>
<th>$\exp(v) = 1.164$</th>
<th>$\exp(v) = 1.215$</th>
<th>$\exp(v) = 1.264$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Catch RAC</td>
<td>Catch RAC</td>
<td>Catch RAC</td>
</tr>
<tr>
<td>40</td>
<td>500,000* 0.337</td>
<td>500,000* 0.341</td>
<td>500,000* 0.346</td>
</tr>
<tr>
<td>50</td>
<td>850,000* 0.260</td>
<td>850,000* 0.266</td>
<td>850,000* 0.271</td>
</tr>
<tr>
<td>60</td>
<td>1,337,400 0.268</td>
<td>1,323,900 0.275</td>
<td>1,311,600 0.282</td>
</tr>
<tr>
<td>70</td>
<td>1,339,500 0.324</td>
<td>1,326,000 0.333</td>
<td>1,313,700 0.341</td>
</tr>
<tr>
<td>80</td>
<td>1,344,400 0.408</td>
<td>1,330,800 0.419</td>
<td>1,318,400 0.429</td>
</tr>
<tr>
<td>90</td>
<td>1,356,600 0.481</td>
<td>1,342,800 0.493</td>
<td>1,330,200 0.505</td>
</tr>
</tbody>
</table>

Note: RAC denotes ray average cost; * indicates the catch is equal to the physical capacity constraint.
The RAC estimate obtained from the cost survey data is considerably higher than the minimum RACs reported in table 12. Three key factors can explain this difference. First, the RAC cost minimizing catch per vessel as predicted by our analysis is considerably larger than the actual catch per boat reported in the PacFIN database. PacFIN data indicate that in 2004 the average total harvest per vessel was 433,800 pounds (see table 9). Table 12 suggests that 50- and 60-foot vessels attain a minimum RAC at a harvest that is roughly two times larger for 50-foot boats and three times larger for 60-foot vessels. Increasing the catch per vessel will reduce fleet size and, in turn, reduce the total fixed costs incurred by the groundfish fleet. Second, the analysis reveals that some capital types incur higher costs per landed pound than others. Results suggest that vessels in the range of 50-60 feet in length attain the lowest RAC. Consolidating the fleet-wide groundfish harvest onto the most efficient vessels types will further reduce the cost per harvested pound of groundfish. A third source of cost saving arises in the form of a pure efficiency gains, although our results reveal only modest cost inefficiency in the sample data.

Sensitivity to Model Assumptions

We next consider the sensitivity of the results to model assumptions, particularly the assumptions for physical harvesting capacity. We repeat the above analysis under the assumption that physical harvesting capacity is 25% lower than reported in table 1. The results indicate only small changes in the predicted costs savings (59.35%) under IFQs. Note that the results in table 12 indicate that the physical capacity constraint does not bind for 60-90-foot length classes. Thus under a tightened physical capacity constraint, the model suggests an IFQ-regime fleet consisting of larger boats; however, only a slightly larger RAC ($0.267) is predicted. Relaxing the physical capacity constraint also has small effects on predicted cost savings under IFQs. A 25% increase in the physical capacity constraints raises the cost savings estimate to 64.82% of actual 2004 costs. We note that the cost savings estimates increase by roughly 1.5% when \( \exp(\nu) = 1.164 \) and fall by roughly 0.5% when \( \exp(\nu) = 1.264 \).

A second factor that impacts the above results is the mix of groundfish species that is harvested by vessels. Larger vessels have larger per-trip hold capacities and are capable of fishing in more severe weather. While the above results suggest that larger boats incur higher costs per landed pound, they land more fish annually, which can provide an economic advantage, particularly in a fishery with varying annual harvest quotas. This advantage is demonstrated in figure 3.

Figure 3 plots RAC surfaces for 60- and 70-foot vessels under different mixes of DTS and Non-DTS TACs. Beginning in the northwest panel (a) and rotating clockwise, the ratio of DTS to Non-DTS in the harvest vector is reduced from 3/1 to 1/3.

RAC is lower on 60-foot vessels until the total catch reaches the 60-foot vessel capacity constraint at 1.5 million pounds. Additional physical harvest capacity on a 70-foot vessel can be an advantage in instances where the fishery manager announces a particularly large TAC relative to the total harvesting capacity of the active groundfish fleet. In this event, harvesting additional fish on 70-foot vessels, even if this means harvesting fish at higher variable costs, may be preferred to adding additional boats to the groundfish fleet. The downside is that cost can rise sharply at high harvest levels, which offsets the advantages offered by the additional physical capacity.

The figure demonstrates that the rate at which costs rise depends on the mix of targeted species. Our cost estimates indicate that, relative to non-DTS species, DTS species not only have a higher marginal cost for any given vessel type, but that marginal costs increase more steeply than those of non-DTS species. As a result, when the ratio of DTS/Non-DTS is high, as in panel (a), variable costs rise steeply, offsetting the returns from
utilizing large physical harvest capacity. Put another way, when costs rise sharply, average costs on larger capacity boats fall more slowly, reducing the relative advantage of larger vessels. The figure shows, however, that as the proportion of Non-DTS in the harvest mix increases, the cost surfaces flatten out. The upshot is that average costs per pound and value of harvesting flexibility offered on larger vessels will be more pronounced when the harvest mix is tilted toward non-DTS species.

Figure 3. Cost, Capacity, and Species Mix