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# Property rights and the efficient extraction of common pool resources: evidence from west coast groundfish

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**Disciplines**

Aquaculture and Fisheries | Econometrics | Economic Policy | Industrial Organization

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**JEL Classification:** Q22, L25, L51

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[*] In memoria.

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# 1 Introduction

Dissipation of economic rent under poorly defined property rights has plagued global fisheries resources for decades (Gordon, 1954; Scott, 1955; Hardin, 1968; Ostrom, 2008). Regulators have attempted to address the problem by controlling the quantity of factor inputs or fishing *effort* allocated to the resource, e.g., controls on the number of vessels and their size, limits on fishing time, controls on the type and quantity of gear deployed. Input control regulation, known alternatively as controlled access, may slow but generally dos not prevent overcapitalization and rent dissipation and instead is associated with a costly race to fish, low product quality and price, unsafe fishing conditions, and habitat degradation (Arnason, 1993; Casey et al., 1995; Homans and Wilen, 1997, 2005). Rights-based (RB) management approaches, such as individual fishing quotas (IFQs), refocus regulation to the control of the harvest. RB approaches provide incentives to minimize the cost of harvesting annual quotas and promise to realign fleet harvesting capacity with the sustainable catch (Montgomery, 1972; Segerson and Squires, 1990; Weninger, 1998). Claims of the sizable economic benefits from adopting RB management are pervasive (Arnason, 1990; Wang, 1995; Weninger, 1998; Batstone and Sharp, 2003; Homans and Wilen, 2005; Brinson and Thunberg, 2016) while studies that measure economic gains and validate claimed efficiency benefits are rare. This paper fills this gap.

Evaluation of RB fisheries management reform faces several challenges. A first is limited data; quantifying changes in revenues and costs as fishermen adjust to changing economic incentives under RB operating rules is data demanding. Our data include the universe of vessel operations that participated in the US West Coast groundfish limited entry trawl fishery, hereafter the groundfish fishery, from 2009-16. The data period spans two years prior to and six years following the implementation of IFQ regulations (data collection is overseen by the Northwest Fisheries Science Center). We observe annual vessel-level harvests across all groundfish species, revenue, variable and fixed operating expenses, capital costs, multiple vessel characteristics, crew labor, and other factors. Observing the universe of participating vessels across an 8-year span allows evaluation of multiple aspects of economic performance that was previously not possible.[1]

Delayed rationalization highlights a second challenge in the evaluation of RB management reform. A significant component of the rent gains take the form of costs saving from removing redundant capital that built up under the period of controlled access regulation. The ground-

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[1] We are aware of one study that measures changes in cost efficiency and fishery rent using pre- and post-IFQ regulation data on harvesting costs. Grafton et al. (2000) study a sample of 107 vessels that participated in the B.C. groundfish fishery during three separate years; 1988 (two years before an individual vessel quota regulation was implemented), 1991 (the year the regulation was implemented) and 1994 (two-years following implementation). A larger literature measure (only) changes in technical efficiency pre- and post-IFQ regulation using primal models (e.g., Solís et al. (2014)).

fish fishery, from 1982-2010, experienced a build-up of its fishing fleet, stock depletion across multiple groundfish species, and reductions in profitability.[2] Entry restrictions and bi-monthly landings limits capped fishing mortality but did not prevent an *economic* tragedy of the commons. In 2003 the US Congress financed a $46-million permit buyback program that removed 91 vessels (representing 35 percent of total limited entry permits) from the groundfish and associated fisheries. This policy likely improved the economic outlook for groundfish fishermen, but only temporarily (Warlick et al., 2018; Lian et al., 2010). In January 2011, the Pacific Fisheries Management Council replaced input control regulation with IFQs; shares of annual groundfish quotas were allocated gratis to eligible fishermen; entry restrictions and bi-monthly landings limits were dropped.

IFQ regulations provide incentives to align fleet harvesting capacity with annual catch limits (**?**). As was the case in West Coast groundfish, a common motive for adopting RB regulations is fleet rationalization, i.e., the process of removing excess vessel capital that accumulated under controlled access regulations. The transition from the initially overcapitalized to the RB-equilibrium fleet structure can however takes years, even decades, to complete.[3] Our data reveal a pattern of delayed fleet rationalization. In light of such delays it is imperative that structural analysis be conducted to characterize and measure the state of the rationalization process so that long-term cost savings from rationalization can be identified.

A third challenge is that ours is an event study; we seek to compare before and after economic performance but in an environment in which the abundance, growth, and spatial migration of groundfish stocks is not directly observed and potentially nonstationary. Failing to control for this component of productivity change will confound efficiency measurement with important implications for our results.[4] We control for the effects of unobserved stock abundance on fleet productivity with a latent spatial-temporal productivity component that is estimated within a stochastic frontier model. We extend a time-varying model of efficiency first developed by Battese and Coelli (1988) and Kumbhakar (1990) to allow for spatial variation in unobserved productivity effects in particular the latent groundfish stock abundance. Our approach isolates

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[2] Section 2 provides additional details of historical developments in the groundfish fishery. See Warlick et al. (2018) for a complete account.

[3] **?** document this remarkably consistent pattern wherein, following the introduction of RB regulations, oversized fleets in Alaska, British Columbia, Chile, Norway, Denmark, Australia, Iceland, the Faroe Islands, and US fisheries decline in size over periods of 10-20 years (see also Grafton et al. (2000), Turner and Weninger (2005) and Munro et al. (2009)).

[4] The problem we face is that stock assessments methods only *estimate* the size and species composition of the groundfish stock. Methods often rely on industry productivity to proxy for changes in unobserved abundance, which likely introduces a circular interdependency with changes in productivity affecting abundance estimates and abundance estimates affecting productivity measures. Stock assessments derived exclusively from fishery-independent data are sometime available, but rarely at the spatial-temporal scale at which fishing operations are carried out. We avoid this stock-abundance versus fishing productivity identification dilemma with a structural empirical estimation that treats the groundfish stock as a latent variable.

changes in economic performance that are attributable to IFQ regulatory reform. We measure changes in technical efficiency, capital investment/divestment incentives, and resource rent following the switch to IFQ regulations.[5]

Our results show that vessel entry restrictions and bi-monthly landings limits prevented full rent dissipation in the groundfish fishery. However, at the time IFQs were adopted, fleet size and harvest capacity far exceeded sustainable groundfish catch levels. During the six years under IFQs, fleet size declined 28.3% from 120 vessels in 2011 to 86 vessels in 2016. At the same time total landings increased by roughly 22% from 53.14 million pounds to 64.98 million pounds per year. We estimate average annual rent during the controlled access regulatory period (2009-10) at $19.95 million per year. Annual rent increased to $25.39 million per year in the first two years of the IFQ regime, 2011-12, increased again to $26.74 million per year during 2013-14 and to $31.26 million per year in 2015-16.[6]

Under the pre-IFQ regulations, most (73.1%) active vessels operated in a region of increasing returns to size. Our analysis of returns to size and vessel capital shadow prices confirm that vessel owners faced incentives to divest capital under the IFQ regulation. Measured economies of size and capital shadow prices have both moved toward levels predicted under an IFQ-regime equilibrium fleet structure. However, we find evidence that the capital adjustment process remained incomplete six years after the switch to IFQs. The implication is that further cost savings and rent gains are pending as of 2016; the transition to the IFQ-regime fleet structure was incomplete six years after the IFQ program began. As other management changes occur, e.g., modifications to annual catch limits as stocks rebuild and opening rockfish conservation areas, additional adjustments are likely in the fishery.

Our results regarding operation-specific technical efficiency do not conform with earlier literature. Grafton et al. (2000) report that average technical efficiency increased three years after IFQs were introduced in the B.C. halibut fishery.[7] Schnier and Felthoven (2013) find that technically inefficient vessels were more likely to exit the Bering Sea and Aleutian Island crab

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[5] At the same time, a cooperative management program was implemented for the at-sea mothership trawl fleet. In principle, a cooperative management program will internalize the costs associated with ill-defined property rights in common pool fishery resources. This study examines harvesting efficiency and general economic performance among vessels that participated in both the IFQ regulation and under the cooperative management program. We cannot separately identify the effects of the simultaneous introduction of the cooperative and IFQ regulation.

[6] During 2011-13, quota owners could temporarily lease landings rights to other vessel operators but could not permanently transfer quota through sale. The decision to prohibit permanent quota trades during the first two years was intended to allow fishermen opportunity to learn how the fishery will function under catch shares management so they may be better able to assess the value of individual fishing quotas before trading begins. Permanent transfers through sales began in 2014. We are unable to determine if restrictions on permanent quota transfers impacted capital restructuring.

[7] The Grafton et al. (2000) finding is based on a comparison of technical efficiency among 11 vessel operations sampled from the pre-IFQ fishery and 21 (potentially) different vessels sampled in post-IFQ fishery. The power of the test used to compare technical efficiency across regulatory regimes may be impacted by limited data.

fishery when the IFQ regulation began. Brandt (2007) compares technical efficiency among surviving, exiting, re-entering vessels in the Mid-Atlantic clam fishery and finds that vessels that re-entered during a period preceding the introduction of IFQs were less efficient than vessels that exited under the IFQ regulation, and that both vessel classes were less efficient than those that remained under the IFQ regulation.

We do not find evidence that technical inefficiency played an important role in fleet downsizing. Our results indicate that economies of size on the other hand is strongly inversely correlated with vessel exit under groundfish IFQs. Smaller vessels were also more likely to exit the fishery, as were vessels that operated in relatively less productive geographical regions. We conclude that multiple factors likely influence a decision to exit an overcapitalized fishery under IFQ regulations. Further research on this topic is warranted.

## 2 Background

The West Coast groundfish fishery is managed by the Pacific Fisheries Management Council (PFMC), a stakeholder body that formally advises the National Marine Fishery Service (NMFS) on management of fisheries in federal waters located 3 to 200 miles off California, Oregon, and Washington. Over 87 species of groundfish are found on the continental shelf and slope, with multiple species that inhabit common geographical regions and depths. The commercial fishery is comprised of four sectors: limited entry trawl, sablefish endorsed limited entry fixed gear, non-endorsed limited entry fixed gear, and open access. Tribes located in the state of Washington also participate in the West Coast groundfish fishery. The limited entry trawl component received all whiting allocation and over half of the other groundfish species allocated to the four commercial sectors. See Warlick et al. (2018) for a detailed history of the fishery. This paper focuses on the shoreside trawl and the at-sea whiting sectors of the fishery.

The modern history of management began in 1976 with the passage of the Magnuson-Stevens Act. Throughout the 1960s and 1970s, factory trawlers from foreign nations such as Japan, Russia, and Korea operated in this fishery. The Magnuson-Stevens Act established a 200-mile Exclusive Economic Zone off the shore of the United States, thereby defining the groundfish fishery as a domestic resource. Policies such as the Capital Construction Fund promoted acquisition of vessels and gear by domestic fishermen. By the early 1980s, the West Coast groundfish fleet size and accompanying harvest had reached unsustainable levels; West Coast groundfish landings peaked at 139.95 thousand metric tons (mt) in 1982.[8] In 1994, the NMFS implemented

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[8] In 1982 the 139.95 thousand mt of groundfish landed included 61,594.8 mt of rockfish and only 7,973.5 mt of whiting. In 2012 groundfish landings on the West Coast were 92,188.4 mt, or 66% of the 1982 peak level. The species composition was however very different. Whiting accounted for 67,635 mt in 2012, or over 70% of landings at an average price of $0.14 per pound. Due to overfishing of some groundfish species, rockfish landings were only 4,787

a limited entry program for the groundfish fishery. The threshold catch history required to obtain a limited entry permit was fairly low, and therefore the program did not sufficiently reduce harvesting capacity.

Seven species of groundfish were declared overfished in 1999 and management steps were taken to rebuild these species' stocks.[9] The use of time- and space-based prohibitions on fishing became common. In 2002, the PFMC took the unprecedented step of prohibiting fishing at large portions of the continental shelf where most of the overfished species live.

In 2000 the Scientific and Statistical Committee of the PFMC declared overcapitalization the number one problem in the West Coast groundfish fishery. The permit buyback program was implemented in 2003 for the limited entry groundfish trawl fleet. Ninety-one limited entry trawl permits were purchased reducing the total number of permits to 180. The trawl buyback program significantly reduced the number of active vessels in the commercial trawl fishery, and as a result, catch and revenue per vessel from groundfish increased in 2004 (Warlick et al. (2018)).

In September 2003 the PFMC voted to consider implementing an IFQ management program in the West Coast groundfish trawl fishery. In November 2008, the PFMC voted to implement the management plan. The main goals of the new regulation are to maintain landings levels for species with healthy stocks, minimize bycatch of species with depleted stocks, and further reduce harvesting capacity in the fishery.

Pre IFQ regulations in the groundfish fishery included a combination of two month landings limits (called trip limits), gear restrictions, area closures, and observer coverage on about 20% of trips targeting groundfish. A permit owner that did not fish his/her allocation of a species during a two month period lost that allocation. Vessels that fished with a trawl endorsed limited entry permit were required to use trawl gear (with the exception of a pilot program in Morro Bay, CA which allowed sablefish to be caught with fixed gear).[10] The constraints on harvesting operations under the bi-monthly landings limits is further investigated in Section 5.2.2.

Management under the IFQ system is based on monitoring catch (as opposed to landings). Observer coverage is required on 100% of trips targeting groundfish. Groundfish fisherman must possess or acquire quota for each pound of fish caught. Individual fishermen were allocated quota based on landings during a historical period. During 2011 and 2012, fishermen could transfer quota to other fisherman by selling *pounds* associated with their initial quota allocation. Permanent sales of quota shares, i.e., permanently transferring the quota pounds of a species

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mt in 2012.

[9] A species is deemed overfished if its biomass falls below 25% of its estimated unfished biomass. The seven overfished species were yelloweye rockfish, canary rockfish, widow rockfish, darkblotched rockfish, boccacio, cowcod, and Pacific Ocean perch.

[10] During 2009 and 2010 a limited number of vessels participating in a pilot program. Fixed gear-caught sablefish is considered a higher quality product than trawl-caught sablefish and typically sells for a higher price.

allocated each year, began in 2013. Fishermen have more flexibility in choosing the gear type used for harvesting groundfish. For example, hook and line gear or pots can be used for sablefish harvested with trawl quota.

## 3 Data

Our data combines annual operating expenses, collected under the Economic Data Collection (EDC) program, and landings and revenue data, collected from the Pacific Fisheries Information Network (PacFIN) database. The data are available for all vessels participating in the groundfish fishery; 158 unique vessel operations in all. Additional information on marine fuel prices was obtained from the Pacific States Marine Fisheries Commission.[11]

The EDC data contain all expenses incurred while fishing on the US West Coast during the data period.[12] Vessel owners report fuel, ice and bait expenses, payments to hired captains and crew, food expenditures, and expenses for offloading the catch, among others. The PacFIN database records, at the trip level, vessel- and species-specific landings and revenues for all West Coast landings. Additional revenues from at-sea landings are obtained from the EDC cost survey.[13] Information on days at sea, gear usage, crew size, fuel consumption, and the crew share system is available in the EDC data.

We separate expenses into variable and fixed components. Variable costs include expenditures on crew and captain labor, gear, fuel, bait, food, ice, communications, vessel maintenance and offloading of the trip catch. Fixed annual costs include expenses for moorage, insurance, and vessel association dues.[14]

It is typical, as in our data, to observe wide variation in capital utilization during a given calendar period. For example, the 5'th and 95'th percentile values of reported days at sea in our data are 22 and 160, respectively. Twenty-nine of the 158 unique vessels in the data (38.3%) participated in Alaskan fisheries during 2009-16.

These considerations have implications for measuring economic performance in commercial fisheries. A common view is that vessel capital is a quasi-fixed factor of production (Kirkley and

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[11] Available at http://www.psmfc.org/efin/data/fuel.html.

[12] Vessels that participate in the West Coast shoreside groundfish fishery may also participate in (i) other West Coast shoreside fisheries such as crab and shrimp, (ii) the West Coast at-sea groundfish fishery (where participating vessels almost exclusively deliver whiting to at-sea motherships), and (iii) Alaskan fisheries. Few vessels participate in all of three fisheries, and few participate in the West Coast groundfish fishery only. Participation in Alaskan fisheries is considered when calculating fixed annual operating costs.

[13] At-sea deliveries are made to at-sea processors in the Pacific whiting fishery. At-sea revenues are comprised almost entirely of whiting.

[14] Vessel associations provide service in the form of information provision, networking services, and lobbying of management authorities.

Strand, 1988; Segerson and Squires, 1990).[15] We measure the flow of capital services that are utilized by individual harvesting operations in our data. We denote this capital measure as $k_i$ for operation $i$ and emphasize that its units are 2016 dollars. Appendix A.4 explains how capital services are measured.[16]

Our data include 844 vessel-year observations on 158 unique vessels across eight years.[17] Each vessel is observed for an average of 5.34 years.[18] Vessels range from 27 feet to 149 feet in length. The average vessel spends 91.66 days at sea per year, lands 3.38 million pounds of groundfish, crab and shrimp and earns an annual revenue of $854,170. Descriptive statics for the annual landings, expenses, revenue, and days at sea are reported in Table 6 in Appendix A.1.

As in most commercial fisheries, crew remuneration takes place under a share system where individual crew members are paid pre-determined shares of revenues, in most cases with components of variable costs deducted. The price of labor, as seen by the vessel manager is a share of harvest revenues. Prices of miscellaneous expenses are not available in our data. We therefore include only the price of fuel in our cost specification.

### 3.1 Multiple-species harvest technology

Treating each of the 87 West Coast groundfish as a unique output in a multi-output harvest technology is not practical. To reduce the dimensionality of our estimation, we aggregate, linearly, across several species to form species groups based primarily on species importance in landing and revenue and management focus. Our initial output groupings include: (1) Pacific whiting landed at shore, (2) Pacific whiting delivered to at-sea motherships, (3) dover sole, (4) thornyhead sp., (5) sablefish caught with trawl gear, (6) sablefish caught with pot and longline gear, (7) non-DTS species (DTS indicates dove sole, thornyheads, and sablefish), (8) crab, (9) shrimp and (10) other non-groundfish species.[19] Major non-DTS species include yellowtail

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[15] Empirical models of fishery production often measure the capital input using a *stock* measure such as vessel length. This approach implies that capital services provided by all 50 foot length vessels is identical, regardless of whether they spend 22 or 160 days at sea.

[16] This calculation of capital costs assumes fishing vessels are perfectly malleable, i.e., they can be reallocated to other fisheries or used in non-fishery activities without incurring additional adjustment costs. If adjustment costs are present our approach will overstate vessel capital value (Singh et al. (2006)). Our data suggest the capital malleability assumption is reasonable: groundfish trawl vessels regularly participate in crab and shrimp fisheries; 574 vessel-year observation (68.0 % of our data) harvest crab and/or shrimp in a given year and 91 (10.8%) report landings of both trawl-caught and pot-caught fish in a single year, suggesting that switching across gear types is not prohibitively costly.

[17] One vessel-year combination had missing data on fuel expenses and quantity and was dropped from our analysis.

[18] 18 vessels are observed for one year; 24 for two years; 8 for three years, 5 for four years, 13 for five years, 15 for six years, 21 for seven years, and 54 for all eight years.

[19] The non-DTS group includes all groundfish species, excluding whiting, dover sole, thornyheads and sablefish. Other non-groundfish species include pelagic and highly migratory species and salmon. Species groups 1-7 are

rockfish, widow rockfish, longnose skate, and Pacific cod. These species tend to be caught in shallower waters relative to dover sole, thornyheads and sablefish warranting a separate output category. The major species that comprise the other non-groundfish species category include shad (327,339 pounds in 2012) and squid (54,200 pounds in 2012). Pot- and longline-caught sablefish represent a small share of total landings and revenues (see Table 7 of Appendix A.1).

Models of multi-species harvesting technologies have followed three forms: (1) non-joint in inputs where individual species are assumed to be harvested independently of one another; (2) fixed output proportions, where the vector of harvested species is assumed fixed by relative abundance of individual species stocks, and; (3) a flexible technologies wherein fishermen control the mix of species harvested (see Turner and Weninger (2005); Branch and Hilborn (2008); Singh and Weninger (2009, 2017)). Groundfish fishermen choose where, when, and at what depths to deploy gear. Occasionally they configure trawl gear to harvest shrimp and use fixed gear to harvest crab. These decisions impact the quantity and mix of harvested species and we therefore specify a flexible multiple-output groundfish technology for our estimation.

Testing and measurement of output substitution possibilities is complicated by the unobservability of the groundfish stock abundance at appropriate temporal and geographical scale.[20] In particular, variation in the observed output levels and species mix may be due to deliberate targeting actions of fishermen or natural variation in the unobserved (from the researchers perspective) stock abundance.

A preliminary analysis of trip-level landings by species suggests the technology exhibits harvest jointness for whiting, trawl-caught sablefish, dover sole, thornyheads, and non-DTS, and other groundfish species, and non-jointness in crab, shrimp and pot-caught sablefish species (see Appendix A.5). These assumptions are maintained through the remainder of our analysis.

Finally, a common approach in applied production analysis to impose known properties of cost functions during estimation, e.g., linear homogeneity in input prices, convexity in harvest. The regulatory history of the groundfish fishery and evidence presented below indicate, however, that operating conditions in the groundfish fishery do not match those expected in competitive and unregulated industries. Imposing curvature properties in our regulated fishery environment may be inappropriate. We therefore avoid such restrictions and interpret our cost functional form as a second order approximation to the true cost technology over the domain of harvests, input prices, and capital allocations that are observed in our data. Results are interpreted accordingly.

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included under the West Coast Groundfish Trawl Catch Share Program.

[20] Vessels in our data operate over a latitude range of roughly 13.48 degrees from California to the US-Canadian border.

### 3.2 Groundfish stock effects

The minimum cost of landing groundfish is assumed to vary with harvest quantity, prices of factor inputs (fuel, labor, gear, and vessel capital services), and the abundance of the *in situ* fish stock. Commercial groundfish fishing involves dragging a large trawl net across the sea bottom, or at intermediated depths if pelagic species are targeted. The quantity and mix of species captured depend crucially on stock abundance *under the boat* at the depths the trawl net is dragged (see Branch and Hilborn (2008)). At the annual level, the catch performance of a vessel operation will depend on the ability of the vessel skipper to consistently position the vessel on high concentrations of the species' stocks being targeted.

Factor input substitutions and output transformation relationships will, in general, depend on stock abundance and species mix. Changes in the stock, if uncontrolled, will bias the estimation of a multiple species harvest technology. To see this, consider a two-species fishery and suppose the abundance of one of the species declines over a data period. Estimated output-transformation relationships will represent the data-period average but will not capture the output-transformation relationship at a particular stock mix. Moreover, it will be impossible to determine if changes in the observed harvest mix are due to a changing stock mix or targeting behavior of fishermen. Note finally that unobserved and potentially spatially and temporally heterogeneous stock abundance creates an identification problem in the analysis of harvest efficiency since low costs may be the result of superior management skill or unobserved differences in stock abundance.

We treat unobserved stock abundance, more precisely, its effect on harvest costs, as a latent variable. We estimate the stock effect semi-parametrically. It should be noted that this approach captures all time- and spatial-varying effects on costs, i.e., stock effects are not separately identified from other time- and spatial varying factors that might impact observed costs. We are however able to obtain a time- and spatial-invariant estimate of the best practice costs frontier as well as individual vessel efficiency measures.

## 4 Model

Let $C(h,w,k,X)$ to denote variable cost for a representative vessel operation: $h$ is an $M \times 1$ vector of species-specific harvests, $w$ is a vector of factor input prices, $k$ denotes quasi-fixed capital, and $X$ is a stock abundance vector that is conformable with $h$. The production period is a single regulatory cycle, which in our case, is a year. For simplicity, we assume $X$ is fixed during the production period.

The fishery is regulated with species-specific quotas which require that harvest is matched with quotas at the individual species level. We assume a frictionless quota trading market exists and use $r$ to denote the vector of annual quota lease prices.

Annual profit for a representative vessel operation is given as,

$$\max_{h,k}\,(p-r)h - C(h,w,k,X) - w_k k,$$

where $w_k$ is the unit capital rental price. The necessary conditions for an interior solution to the above problem plus an equilibrium entry-exit conditions can be used to characterize the long-run equilibrium conditions in an IFQ-regulated fishery:

$$p - r = \triangledown_h C(h,w,k,X), \tag{1a}$$

$$w_k = - \ \triangledown_k C(h,w,k,X), \tag{1b}$$

$$0 = (p-r)h - C(h,w,k,X) - w_k k, \tag{1c}$$

where $\triangledown_z$ denotes partial differentiation with respect to the argument $z$.

Condition (1a) determines the optimal per-vessel harvest vector. Condition (1b) identifies the optimal capital size (evaluated at the optimal $h$), and condition (1c) is an equilibrium entry-exit condition that determines the number of participating vessels. It should be emphasized that conditions (1a)-(1c) characterize the IFQ-regime *equilibrium*; we do not expect these conditions to hold precisely at a particular point in time. Rather, the conditions are used to help interpret the state of groundfish fleet in our empirical data, and to gain insight on the changes we observe. In particular, the quota lease price $r$ is absent under an input-control regulation. It is hypothesized that emergence of stock prices under the IFQ regulations will initiate adjustments to per-vessel harvest activity and fleet restructuring. We next use this model to summarize these expected changes.

If capital is a normal factor of production, we have $\triangledown_k C(h,w,k,X) < 0$. Condition (1b) states that marginal reduction in operating costs from an additional unit of $k$ must just offset the unit capital cost. If $w_k < -\triangledown_k C(h,w,k,X)$, the fisherman has incentive to invest in additional capital. When $w_k > -\triangledown_k C(h,w,k,X)$, capital divestment is called for (see Segerson and Squires (1990) for details).

We can use equations (1a)-(1c) to assess size economies. Multiplying condition (1a) by $h$ and combining with (1c) obtains,

$$S(h,w,k,X) = \frac{C(h,w,k,X) + w_k k}{h' \triangledown_h C(h,w,k,X)} = 1. \tag{2}$$

$S(h,w,k,X)$ has been proposed as a measure of multiproduct economies of size (Baumol, 1976; Panzar and Willig, 1977). $S(h,w,k,X) > 1$ indicates operation in a region of increasing returns, i.e., a 1% increase in $h$ will result in a less than 1% increase in annual cost. In an

IFQ fleet structure equilibrium, size economies must be exhausted, i.e., $S(h,w,k,X) = 1$; if not, additional quota trades and harvest adjustments can further reduce costs, thus contradicting the required condition that all gains from quota-trading are exhausted.

Although not emphasized in the representative fisherman model above, a third avenue by which fleet restructuring may proceed is through removal of inefficient capital. Quota holders in an IFQ fishery face a common quota holding cost and therefore must match the efficiency of active quota holders (see also Montgomery (1972)). Our empirical version of the above model will be extended to introduce heterogeneity in efficiency across vessel operations. The model is adopted from the stochastic frontier literature for panel data with adaptations to account for the unique characteristics of commercial fisheries (Battese and Coelli, 1992).[21]

Assume annual groundfish harvest costs take the form:

$$C(h,w,k,X) = c(h,k,w) \times \exp\left(\eta(X,u_i) + \epsilon\right). \tag{3}$$

The term $u_i \geq 0$ is a measure of efficiency for vessel operation $i$ and $\epsilon$ is a symmetric regression error term.

The effect of stock abundance on costs operates through the term $\eta(X,u_i)$. Stock abundance $X$ is however unobserved. To proceed, we assume that the effect of stock abundance on costs varies smoothly across space and time and can be approximated by a differentiable function $\eta(X,u_i) = \eta(s,t) \cdot u_i$ where $s$ indexes space and $t$ indexes time. It is worth noting that while the primary role of $\eta(\cdot)$ in our model is to control for potentially changing abundance, its inclusion will capture all uncontrolled factors influencing costs that vary smoothly with $(s,t)$. Stock abundance effects cannot be separated from these other factors. Our results will be interpreted with this limitation in mind.

We specify the logarithm of $\eta$ as,

$$\eta(X,u_i) = \eta(s,t|\alpha) \cdot u_i + \zeta = \exp\left(\sum_{j=1}^{J} \alpha_j b_j(s,t)\right) \cdot u_i + \zeta, \tag{4}$$

where $b_j(s,t)$ denote known basis functions of $(s,t)$, $\alpha_j$ is a vector of basis coefficients, and $\zeta$ is an approximation error.

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[21] Battese and Coelli (1992) allow firm-level efficiency to vary over time (either positively, negatively or not at all) to reflect common time-varying influences on firm-level productivity, for example, industry wide technological change.

### 4.1 Cost functional form

We specify a deterministic kernel of our cost model as the following log-quadratic function:

$$
\begin{aligned}
\ln c(h,k,w|\beta) = & \beta_0 + \sum_{m=1}^{M} \beta_m h_m + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \beta_{mn} h_m h_n + \beta_w \ln(w) + \frac{1}{2}\beta_{ww} \ln(w)^2 \\
& + \sum_{m=1}^{M} \beta_{wm} \ln(w) h_m + \sum_{m=1}^{M} \beta_{km} \ln(k) h_m + \beta_k \ln(k) + \frac{1}{2}\beta_{kk} \ln(k)^2,
\end{aligned}
\tag{5}
$$

where $\beta$ collects all model parameters.

The functional form in (5) has several advantages. First, it is sufficiently flexible to capture all economic effects needed to characterize the multiple-species groundfish fishing technology (Diewert and Wales (1988); Fuss et al. (1978)). Second, and importantly for our application to a multiple-species fishery, it is defined analytically when one or more species' harvests are zero. This situation occurs at each vessel-year observation in our data. Finally, the functional form is linear-in-parameters which help simplify the estimation of $\beta$. Hereafter, the right-hand side of ((5)) will be expressed compactly as $Z\beta$, where $Z$ collects the cost function arguments.

### 4.2 Maximum likelihood estimation

Let $v_{ist} = \epsilon_{ist} + \zeta_{ist}$ for vessel operation $i = 1,\ldots,I$, fishing location $s$, and year $t$. We assume $v_{ist}$ is an independently and identically distributed normal random variable with mean zero and variance $\sigma_v^2$. We assume vessel-specific cost efficiency in our data follows a half normal distribution; $u_i \sim N^+(0,\sigma^2)$. We assume further that $v_{ist} \perp u_i$, and $(v_{ist}, u_i) \perp Z_{ist}$.

Combining all model components and taking natural logarithms obtains the following estimating equation,

$$
\ln C_{ist} = Z_{ist}\beta + \eta(s,t|\alpha)\cdot u_i + v_{ist}, \qquad \text{for } i = 1,\ldots,I,\ s = s(i,t),\ t = 1,\ldots,T_i, \tag{6}
$$

where $s(i,t)$ denotes the region fished by operation $i$ in year $t$, $T_i$ denotes the years of operation for vessel $i$ and $I$ is the number of unique vessel operations in our data.

Battese and Coelli (1992) derive the density of $e_i = \{\eta_{st} u_i + v_{ist}\}_{t \in T_i}$,

$$
f(e_i) = \frac{\left[1 - \Phi\left(\frac{-\mu_i^*}{\sigma_i^*}\right)\right] \exp\left(-\frac{1}{2}\left[\frac{e_i' e_i}{\sigma_v^2} - \left(\frac{\mu_i^*}{\sigma_i^*}\right)^2\right]\right)}{(2\pi)^{T_i/2}\, \sigma_v^{(T_i-1)} \left[\sigma_v^2 + \eta_i' \eta_i \sigma^2\right]^{\frac{1}{2}}}, \tag{7}
$$

where,

$$\mu_i^* = \frac{\eta_i' e_i \sigma^2}{\sigma_v^2 + \eta_i' \eta_i \sigma^2}$$
$$\sigma_i^* = \frac{\sigma^2 \sigma_v^2}{\sigma_v^2 + \eta_i' \eta_i \sigma^2}.$$

The log likelihood function for the $I$ unique vessels observed in our data is:

$$\begin{aligned}\ln\ L(\theta|\{\ln C_i\}_{i=1}^I) = & \sum_i \ln\left[1 - \Phi\left(\frac{-\mu_i^*}{\sigma_i^*}\right)\right] - \frac{1}{2}\sum_i \left[\frac{e_i' e_i}{\sigma_v^2} - \left(\frac{\mu_i^*}{\sigma_i^*}\right)^2\right] \\ & - \frac{1}{2}\sum_i \left[T_i \ln(2\pi) + (T_i - 1)\ln(\sigma_v^2) + \ln\left(\sigma_v^2 + \eta_i' \eta_i \sigma^2\right)\right].\end{aligned} \tag{8}$$

where $\theta = (\sigma_v, \sigma, \alpha, \beta)$ and $\ln C_i = \{\ln C_{ist}\}_{t \in T_i}$.

The minimum squared error predictor of cost efficiency for operation $i$ is obtained as (Battese and Coelli (1988)),

$$\mathrm{E}[\exp(u_i)] = \left[\Phi\left(\sigma_i^* - \frac{\mu_i^*}{\sigma_i^*}\right) \Big/ \Phi\left(-\frac{\mu_i^*}{\sigma_i^*}\right)\right] \times \exp\left(\mu_i^* + \frac{1}{2}\sigma_i^{*2}\right). \tag{9}$$

Maximum likelihood estimation of equation (8) is conducted with Gauss 18 software. We estimate the full model in equation (5) under the maintained hypotheses regarding jointness and separability across individual species (section 3.1).

# 5 Results

We conduct preliminary tests to inform the structural properties of the multiple-species groundfish technology. A likelihood ratio test is used to evaluate alternative specifications. Table 1 reports the results (see Appendix A.2 for details).

Likelihood ratio tests of cost function structure suggest a more parsimonious form than is shown in equation (5). We find that with the exception of whiting, fuel-harvest cross effects can be dropped from the model. We are also able to drop second order fuel price and capital effects. The null hypothesis that cross effects among groundfish species are equal to zero is rejected at significance level < 0.001. This result is noteworthy in light of the fairly strong collinearity among harvests of groundfish species (variance inflation factors are in the range between 2.07 for the non-DTS species group to 4.77 for trawl-caught sablefish).

Our preferred specification includes first-order effects for fuel price and capital input, first- and second-order effects for all nine landed species (whiting, trawl-caught sablefish, dover sole,

| **Parametric restriction:** | $\chi^2$**-stat** | **p-value** |
|---|---:|---:|
| $\beta_{ww} = \beta_{kk} = 0$ | 4.330 | 0.885 |
| $\beta_{mm} = 0 \; \forall \; m \in M$ | 159.706 | <0.001 |
| $\beta_{mn} = 0 \; \forall \; m,n \in M, \; m \neq n$ | 50.348 | <0.001 |
| $\beta_{wm} = 0 \; \forall \; m \in M$ | 34.022 | <0.001 |
| $\beta_{wm} = 0 \; \forall \; m \neq$ Whit. | 10.472 | 0.767 |
| $\beta_{km} = 0 \; \forall \; m \in M$ | 316.696 | <0.001 |
| $\beta_m = \beta_n \; m,n =$ all Whit. | 16.234 | 0.907 |
| $\beta_m = \beta_{DTS} \; \forall \; m =$ D. Sole, T. Heads, Sblf. | 45.502 | <0.001 |

Table 1: Structural properties of groundfish cost technology. DTS species include dover sole, thornyheads, and sablefish. $w$ and $k$, denote fuel price and capital expenditures; $h$ denotes harvest; and $m$ and $n$ denote species in the set of 10 species groups ($M$).

thornyheads, non-DTS species, other non-groundfish species, crab, shrimp, and pot-caught sablefish), cross-effects for all groundfish species, a fuel price-landings cross-effect for whiting, and capital-landings cross-effects for all species. The parameter estimates, standard errors, and p-values are reported in Table 10 of Appendix (A.2).

## 5.1 Cost efficiency

We specify monomial basis functions in equation (4). The index is normalized to unity at the southernmost latitude (35.27 degrees N. latitude) in January 2011, which is the date that the IFQ regulation began. A value of unity is plotted along the perimeter to aid in interpreting the results. Polynomials of varying degree were considered. Our preferred specification sets $\eta(s,t|\alpha) = \exp(\alpha_s s + \alpha_t t + \alpha_{st} st)$ for vessels that specialize in non-whiting species and $\eta(s,t|\alpha) = \exp(\alpha_t t)$ for vessels that focus on harvesting pacific whiting.[22]

Figure 1 plots the estimate of $\eta(s,t)$ over the latitudinal and temporal range of our data for the non-whiting portion of the groundfish fleet. The estimate of common cost efficiency, hereafter CCE, is lowest in the northernmost region in January 2009. The CCE increases moving from the northern to southern region of the fishery, and during the 2009-16 data period. The increase over time is most pronounced in the southern latitudes.

The true cause(s) of spatial and temporal variation in the CCE cannot be determined from our data. A temporally increasing CCE could signal declining groundfish stock abundance, in which case adjustments to annual quotas may be warranted. An alternative hypothesis is that the requirement that at-sea discards count against quota holdings under the IFQ regulation provided incentives to undertake costly avoidance of fish species for which quota is scarce (Somers

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[22] Data indicate that 599 of the 844 vessel-year observations (70.97%) report whiting harvest shares below 0.25; 222 vessels (26.30%) report whiting harvests shares above 0.75. Only 23 vessel-year observations (2.73%) report whiting harvest shares between 0.25 - 0.75.

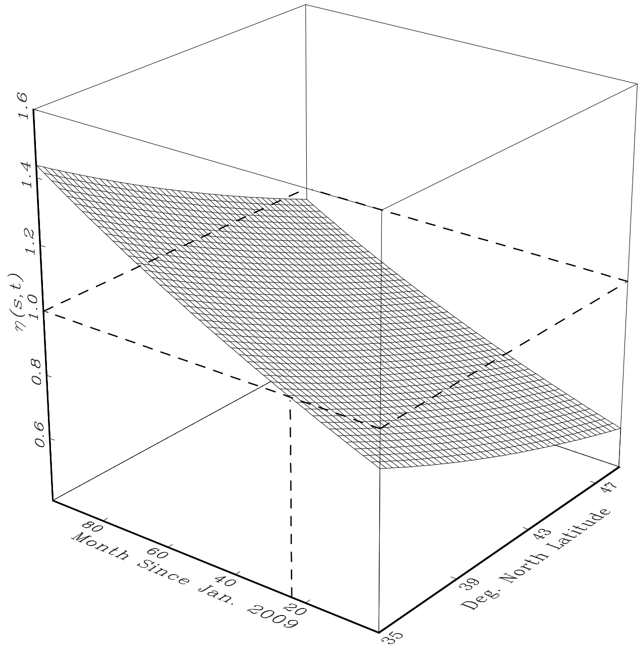

Figure 1: Common Productivity. Figure reports point estimates for common cost efficiency component, $\eta(s,t)$. The index is normalized to unity at latitude 35.27 degrees N. in January, 2011.

et al., 2018).[23] Investigation of these and other explanations is an important topic for future research.

A final observation on our estimate of CCE is that a test of the null hypothesis that its effects are zero, i.e., that $\eta(s,t) = 1$ is rejected at conventional levels of significance (p-values for estimates of $\alpha_s$ and $\alpha_t$ are less than 0.003 (the space-time cross effect is not statistically significant). This finding has implications for measuring the effects of rights-based management reform in fisheries. Suppose it could be confirmed that the temporal trend in the estimate of the CCE is due to declining groundfish stock abundance. In this case, an analysis that ignores CCE effects, i.e., naively sets $\eta(s,t) = 1$ will likely underestimate the efficiency gains attributable to management reform. On the other hand, if the observed trend in the CCE is due to increased costs arising from bycatch avoidance under the IFQ regulation, its effect on fleetwide costs are attributable to management reform and should be included in an assessment of fishery performance. In either case, our results suggest that taking steps to control for unobserved changes in abundance and other factors is crucial for obtaining unbiased estimates of efficiency and eco-

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[23] Singh and Weninger (2009) demonstrate cost savings from discarding fish at sea under a weak output disposability technology. The weak output disposability property cannot be tested in the absence of species-specific stock abundance information.

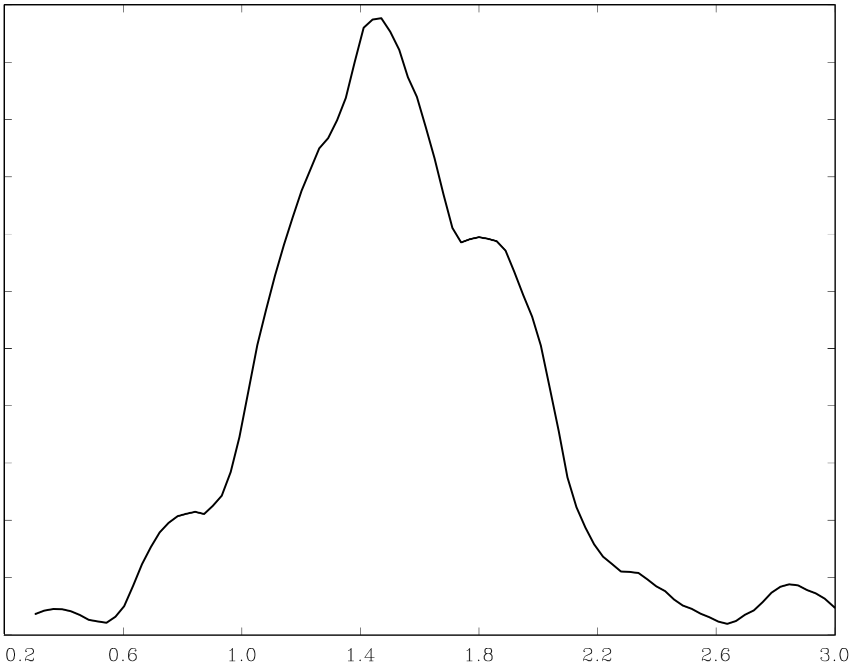

Figure 2: Vessel-specific Efficiency Estimates. Smoothed histograms calculated with an Epanechnikov kernel at reference bandwidth.

nomic performance in fisheries.

The estimate of $u_i$ is interpreted as the ratio of realized costs to stochastic frontier costs conditional on the common cost efficiency component. As is common in applied stochastic frontier analysis, we find substantial cost inefficiency at the vessel level. Figure 2 plots the empirical distribution of estimated $u_i$ for the 158 unique vessels in our data. The results show that the bulk of the inefficiency estimates lie between 0.6 and 2.6. The implications of cost efficiency heterogeneity for fleet adjustments are investigated in Section 5.2.4 below.

The next sections evaluate economic incentives of groundfish fishermen. These incentives are measured from our fitted cost function and are generally functions of observed harvests, factor input prices, space and time, and the estimated parameters. We calculate effects of interest for each vessel-year observation and report summary statistics.[24] To ease notation we use $n$ to index individual observations in our data. It should be noted that $n$ summarizes information on the vessel operation $i$, the location of fishing, $s$ and the observation year $t$.

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[24] An alternative approach is to evaluate economic effects of interest at the mean of the data. This approach masks important insights for fleet restructuring due to considerable differences in the quantity and mix of harvested species among vessel operations.

## 5.2 Economic effects of IFQ regime

### 5.2.1 Capital investment

Recall that capital is measured in units of annual capital expenditures (dollars). The necessary condition for optimal capital employment (equation (1b)) must be modified to match our empirical data. Based on our empirical specification, the capital expenditure-cost elasticity is derived as,

$$\varepsilon_{nk} = \frac{\partial lnC(\cdot)}{\partial lnk_n} = \beta_k + \sum_{m=1}^{M} \beta_{km} h_{n,m}.$$

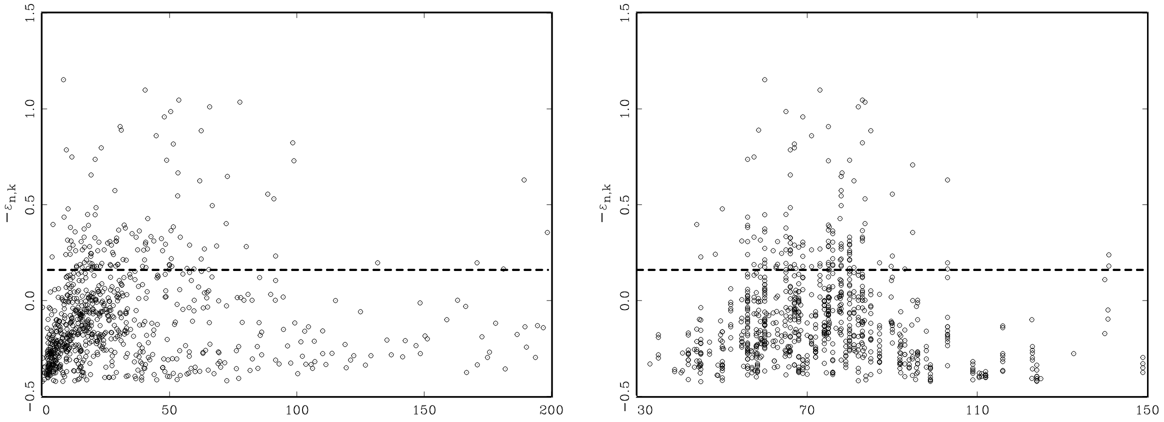
where $h_{n,m}$ denotes landings of species $m$ in observation $n$.

The capital allocation for observation $n$ is optimal when $-\varepsilon_{nk}$ is equal to the ratio of annual capital costs and annual variable costs, $\frac{w_k k_n}{C_n}$. In this case, the marginal reduction in variable cost from the additional capital is just offset by the additional capital expenditure. Estimating the latter is complicated given that there is wide variation in capital utilization in our data. We proceed by selecting vessel operations that fished 75% or more of their estimated maximum days at sea in year $t$ (27 observations satisfy this criterion). The average value $\frac{w_k k_n}{C_n}$ for this sub-sample is 0.16 (with standard deviation, 0.16). We use this average value as a benchmark to characterize incentives to adjust vessel size, i.e., values of $-\varepsilon_{nk} \approx 0.16$ indicate approximate optimal capital size; values for $-\varepsilon_{nk} > (<)\ 0.16$ indicate incentives to invest (divest) vessel capital given the observed harvest, input prices, location of fishing, and fishing date.

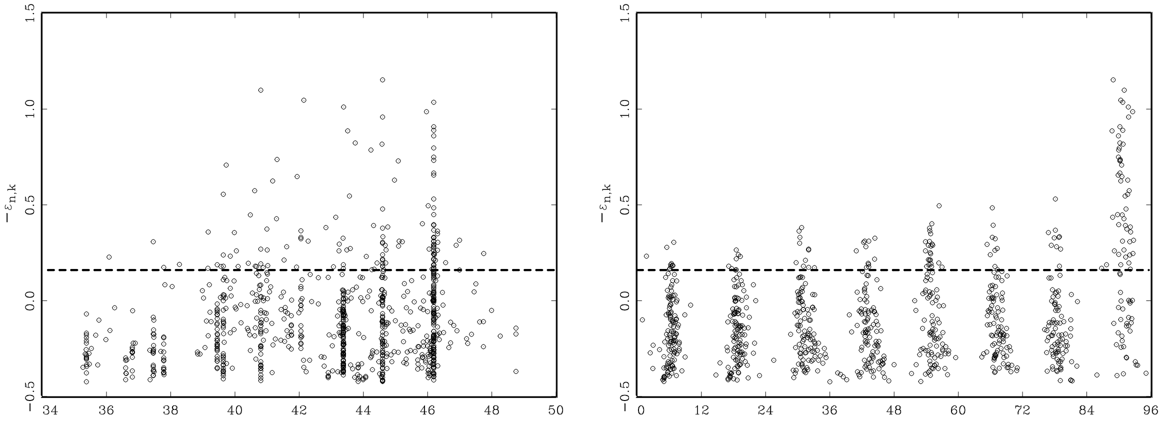
Panels (a)-(d) of Figure 3 plots point estimates of $-\varepsilon_{nk}$ against, respectively, annual capital expenditures (Panel (a)), vessel length (Panel (b)), the latitude of the landing port (Panel (c)), and the cumulative month since January 2009 (Panel (d)). In Panel (a) we see that $-\varepsilon_{nk}$ tends to increase with annual capital employed (simple correlation is 0.19). Panel (b) shows a weak correlation between vessel length and our estimate of $-\varepsilon_{nk}$. The simple correlation is -0.084 suggesting that incentives to adjust individual vessel size may be weak relative to the incentive to adjust capital utilization (panel (a)).

Panels (c) and (d) of Figure 3 plot $-\varepsilon_{nk}$ against space and time. The pattern in Panel (c) shows positive correlation with northern latitudes (simple correlation is 0.334). The pattern in Panel (d) shows that a significant number of groundfish vessels faced incentives to divest capital at harvest quantities observed during the earlier data years (simple correlation is 0.19). Trends indicate that as capital exited the fishery, and catch was consolidated onto fewer boats, the incentive to divest capital eased. Additional investigations find that vessel capital is a normal factor of production at larger harvest quantities observed in our data; the simple correlation between $-\varepsilon_{nk}$ and annual landings is 0.21.

Summarising, results suggest that a significant number of groundfish vessels faced incen-



(a) Capital Exp. ($'000) (b) Vessel Length (feet)



(c) N. Latitude (d) Cum. Month: 2009−16

Figure 3: Capital-Cost Elasticity

tives to divest capital particularly at harvest quantities observed in the early data years. Trends suggest that as the catch per vessel increased, the incentive to divest capital declined.

### 5.2.2 Economies of size

To gain a sense of the extent to which bi-monthly landings limits under the controlled access regulation constrained harvesters ability to exploit economies of size, it is instructive to compare pre- and post-IFQ annual landings. We consider the major groundfish species, dover sole, longspine thornyheads, and sablefish in the northern region of the fishery. Bi-monthly sablefish landings limits allowed a total of 133,000 pounds per vessel in 2010; in 2016, five vessels landed over 275,000 pounds of sablefish. Annual dover sole landings were capped at 650,000 pounds per vessel in 2010; five vessels landed over 1,300,000 pounds of dover sole in 2016. Annual landings of longspine thornyheads were capped at 112,000 pounds per vessel in 2010; in 2016, five

| Period | N | $\overline{S}$ | 10% | 25% | 50% | 75% | Boats |
|---|---|---|---|---|---|---|---|
| 2009-10 | 243 | 3.03 | 0.99 | 1.25 | 1.80 | 2.77 | 130 |
| 2011-12 | 218 | 2.20 | 0.87 | 1.13 | 1.49 | 2.62 | 122 |
| 2013-14 | 202 | 1.81 | 0.86 | 1.06 | 1.35 | 2.13 | 110 |
| 2015-16 | 173 | 3.53 | 0.70 | 0.98 | 1.40 | 2.34 | 95 |
| All Years | 836 | 2.64 | 0.87 | 1.11 | 1.56 | 2.46 | 158 |

Table 2: Economies of size summary statistics. Eight extreme estimates ($S_n > 50$) are dropped. $N$ denotes the number of vessel-year observations; $\overline{S}$ denotes annual landings-weighted average economies of size.

vessels landed over 318,000 pounds of longspine thornyheads.

Removing bi-monthly landings limits, in addition to improving economies os size, may have allowed vessel operators to exploit economies of specialization in harvesting. A Herfindahl-Hirschman Index of annual harvest shares for groundfish species indicates a sample mean (median) value of 0.56 (0.42) in 2009-10. In the first two years of IFQ regulations, the sample mean (median) index value jumps to 0.65 (0.57).

Table 2 reports the landings-weighted averages and percentile values of the $S_n$ estimates. We report results for the full sample (with outliers removed) and for four two-year subperiods: the pre-IFQ period, 2009-10 and the remaining IFQ regulatory regime grouped into two-year intervals. Recall that during the first of these intervals, 2011-12, IFQ regulations did not permit permanent transfers of quota shares. The final column in Table 2 reports the number of unique vessels that operated in the fishery during each subperiod.

The landings-weighted average value of $S_n$ for the full data period is 2.64 suggesting that a significant component of our sample vessel operate under increasing returns to size; aggregate catch could be consolidated onto fewer vessels which should further reduce groundfish harvesting cost. From Table 2 we see that $S_n$ has declined under the IFQ regulation, with the largest decline occurring during 2011-12. With few exceptions, percentiles of the $S_n$ distributions move over time toward the size-efficient benchmark, $S_n = 1$. Notice that the trend toward $S_n = 1$ takes place as participating vessels declined from 130 in 2009-10 to 95 in 2015-16 (Table 2).

Figure 4 plots smoothed histograms of $S_n$ estimates for vessel-year observations falling into the pre-IFQ management regime (2009-10), the first two years of IFQ management (2011-12), and the subsequent four years (2013-16). The right-skewed distributions confirm that a significant portion of the groundfish fleet operated in a regions of increasing returns throughout the data period. The figure also shows that size economies distributions consistently place more mass on values near unity as the IFQ regime progressed and the groundfish fleet downsized. That is, the trend toward efficient utilization of vessel capital with $S_n = 1$ is apparent. The largest shift in the scale efficiency distributions appears to take place immediately following the

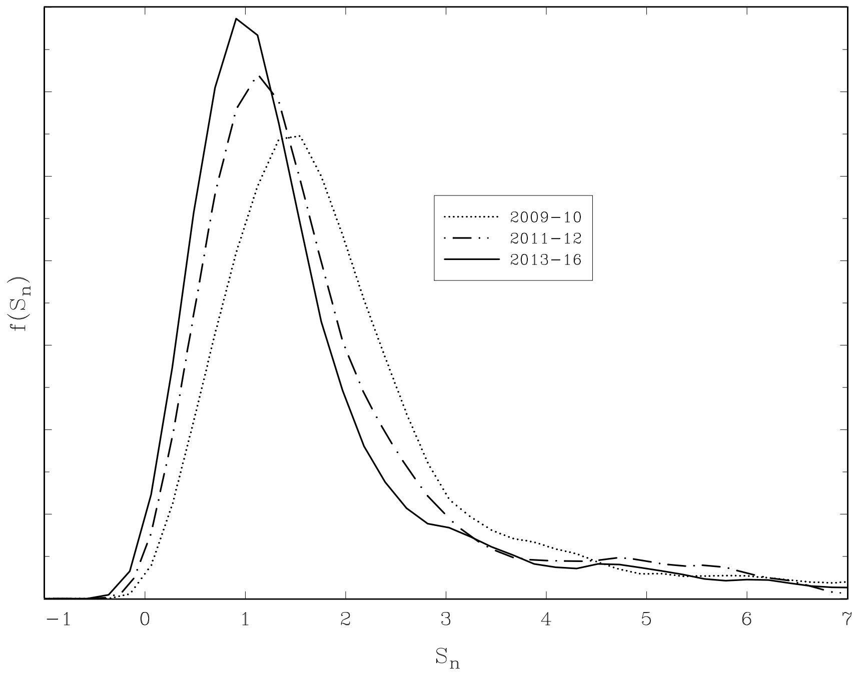


Figure 4: Economies of Size. Smoothed histograms calculated with an Epanechnikov kernel at reference bandwidth.

switch to the IFQ regulation.

The results in Figure 4 demonstrate expected changes in size economies under the IFQ regulation. The right skewed distribution in 2013-16 implies that untapped economies of size and additional cost savings may still emerge in the groundfish fishery.

### 5.2.3 Rent generation

The equilibrium condition in (1c) asserts that economic profit evaluated at the virtual price vector $p-r$ will equal zero in equilibrium. Condition (1a) shows that equilibrium quota prices equate quota lease prices to the marginal profit from an additional unit of harvest. The quota regulation generates resource rent that can be calculated as $\sum_m r_m Q_m$ where $Q_m$ denotes the species $m$ quota. We do not observe quota trading prices directly; we use our groundfish cost model to estimate sample average values of $p - \nabla_h C_h(h,w,k,X)$ which we report in Table 11 in Appendix A.3. Alternatively, fishery rent can be calculated directly as total revenue generated less the total fleet harvesting cost. This latter approach does not rely on the equilibrium assumption and also allows us to isolate rent associated with groundfish harvesting only. For this calculation we use the fitted cost model to estimate variable harvest costs at observed groundfish

| **Period: 2009-10 ($N$ = 244).** | Mean | Std. | 10% | 50% | 90% | Annual Total |
|---|---|---|---|---|---|---|
| Harvest (mill. lbs.) | 1.96 | 3.06 | 0.14 | 0.66 | 5.96 | 239.49 |
| Revenue ($‘000) | 416.91 | 313.95 | 103.62 | 383.39 | 688.29 | 50,863.14 |
| Cost ($‘000) | 252.65 | 189.74 | 70.95 | 209.77 | 463.73 | 30,823.02 |
| Profit ($‘000) | 163.50 | 163.22 | 6.68 | 147.90 | 324.02 | 19,947.41 |
| AC G.F. ($N$=182) | 0.30 | 0.73 | 0.20 | 0.35 | 0.84 | - |
| AC Whit. ($N$=62) | 0.07 | 0.03 | 0.05 | 0.07 | 0.12 | - |

| **Period: 2011-12 ($N$ = 219).** | Mean | Std. | 10% | 50% | 90% | Annual Total |
|---|---|---|---|---|---|---|
| Harvest | 2.74 | 4.68 | 0.07 | 0.50 | 10.21 | 299.82 |
| Revenue | 597.06 | 561.39 | 83.42 | 420.82 | 1,272.77 | 65,378.15 |
| Cost | 349.59 | 327.05 | 79.85 | 236.25 | 729.27 | 38,280.14 |
| Profit | 242.95 | 271.44 | -14.08 | 156.31 | 672.11 | 25,388.14 |
| AC G.F. ($N$=163) | 0.48 | 1.88 | 0.32 | 0.52 | 2.06 | - |
| AC Whit. ($N$=56) | 0.08 | 0.03 | 0.05 | 0.07 | 0.11 | - |

| **Period: 2013-14 ($N$ = 193).** | Mean | Std. | 10% | 50% | 90% | Annual Total |
|---|---|---|---|---|---|---|
| Harvest | 3.49 | 6.01 | 0.06 | 0.43 | 13.37 | 336.92 |
| Revenue | 689.92 | 677.74 | 84.57 | 438.56 | 1,697.23 | 66,577.45 |
| Cost | 417.07 | 402.58 | 75.82 | 270.51 | 982.16 | 40,246.86 |
| Profit | 263.42 | 309.69 | -25.81 | 153.99 | 676.48 | 26,736.75 |
| AC G.F. ($N$=146) | 0.49 | 0.74 | 0.35 | 0.58 | 1.92 | - |
| AC Whit. ($N$-57) | 0.07 | 0.02 | 0.04 | 0.07 | 0.10 | - |

| **Period: 2015-16 ($N$ = 178).** | Mean | Std. | 10% | 50% | 90% | Annual Total |
|---|---|---|---|---|---|---|
| Harvest | 4.57 | 8.09 | 0.13 | 0.83 | 14.95 | 406.56 |
| Revenue | 886.41 | 735.56 | 123.77 | 666.38 | 1,880.96 | 78,890.15 |
| Cost | 516.50 | 427.97 | 99.08 | 396.38 | 1,051.32 | 45,968.79 |
| Profit | 351.23 | 369.87 | -1.63 | 234.63 | 818.51 | 31,259.29 |
| AC G.F. ($N$=131) | 0.47 | 0.57 | 0.32 | 0.50 | 1.44 | - |
| AC Whit. ($N$=47) | 0.05 | 0.03 | 0.04 | 0.06 | 0.08 | - |

Table 3: Per-Vessel Harvest, Revenue, Cost, Economic Profit. AC - average cost per pound. The reported mean value (AC only) is weighted by vessel harvest share. All monetary values are expressed in USD 2016.

species landings with crab and shrimp landings set to zero. We assume vessel capital costs and fixed operating costs are proportional to the days at sea harvesting groundfish species relative to total days at sea. Profit calculations subtract reported costs of observers, which we interpret as a real resource cost of operating the IFQ management program.[25]

Table 3 reports summary statistics for per-vessel aggregate harvests (all species except crab and shrimp), revenue, cost, and profit. We also report landings-weighted cost per harvested

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[25] Average observer expenses in our data are $11,533 per-vessel, per-year.

pound (AC) for vessels that focus on groundfish fishing (harvest mix made up of >75% groundfish species) and vessels that specialize in harvesting pacific whiting (harvest mix made up of >75% whiting). Results are reported across two-year subperiods.

Several noteworthy results/trends are indicated in the table. First, the elimination of landings restrictions coincide with a significant increase in per-vessel harvest. Pre-IFQ vessels harvested an average of 1.96 million pounds per year. The per-vessel average increased to 2.74 million pounds per year in the first two years of IFQ regulation and continued to increase under the IFQ regime to a high of 4.57 million pounds per year in 2015-16 (233% above pre-IFQ levels). Average revenue and cost per vessel operation follow similar trends.

IFQ regulation also coincides with a significant increase in resource rent. Profit (resource rent) per vessel averaged $163,500 annually during the pre-IFQ period. Rent generated per vessel increased steadily during the IFQ regime to a peak of $351,230 in 2015-16. Furthermore, the per-vessel profit distributions display a persistent right skew and, consistent with our findings regarding size economies, vessels operating under increasing returns earn less rent: the simple correlation between profit and $S_n$ is $-0.139$.

Interestingly, the average cost per pound of harvested groundfish increases under IFQ management (roughly, an $0.18 per pound increase); the landings-weighted average cost per pound for non-whiting species is lowest during 2009-10, at $0.30. This result appears on the surface to contradict the expected effects of management reform. In particular, replacing the bi-monthly landings constraint with IFQs should not increase in average costs. Moreover, as argued above, increases in per-vessel harvest obtained economies of size not exploited under the pre-IFQ regulation. Though Somers et al. (2018) note a sharp decline in at-sea discards under the IFQ regime, representing potentially costly at-sea adjustments by vessels to avoid groundfish species for which quota is scarce (Singh and Weninger, 2009), the explanation for low average costs during 2009-10 is not fully known and warrants future investigation.

Annual totals, reported in the final column of Table 3, show significant expansion of groundfish harvest, revenue, costs, and rent during the data period. Rent generation in the groundfish fishery has been substantial. Total rent generated in 2009-10 averaged $19.97 million per year. In the first two years of the IFQ program annual rent increased to $25.39 million. A small rent increase to $26.74 million per year is indicated during 2013-14, and a sharp increase to $31.26 million per year is estimated for the 2015-16 period.

These rent estimates are not adjusted for the common cost efficiency component of our model. Recall, our estimate of $\eta(s,t)$ suggests harvesting costs increased from 2009-16. An important question is whether and to what extent changes in $\eta(s,t)$ are the result of management reform? If rising costs are the result of costly avoidance of bycatch species that began with IFQs, it is reasonable that we include $\eta(s,t)$ effects in our estimate of rent gains. In this case, the rent estimates in Table 3 are valid.

If the increase in $\eta(s,t)$ over time is due to declining stock abundance, the resource rent estimates reported in Table 3 underestimate the gains attributable to management reform. Our model can be used to calculate by how much. When we hold common cost efficiency fixed at its January, 2010 level, our estimates IFQ annual rent increase. Annual rent during 2009-10 is smaller at \$19.69 million per year. The average rent increase under IFQs is now higher at 8.32% per year; \$25.59 million in 2011-12, \$25.92 million in 2013-14 and \$34.16 million during 2015-16.

### 5.2.4 Fleet rationalization

The number of active vessels in the groundfish fishery declined by roughly 30% under IFQ management, from 124 in 2009 to 86 in 2016. This pattern is consistent with evidence of divestment incentives and operation under increasing returns presented above. Our data reveal however that 28 new vessel-operations entered the groundfish fishery under IFQ regulation (2011-16). To further investigate changes in fleet structure we define three vessel categories: *new entrants*, *exiting vessels*, and *incumbents*. We place each of the 128 vessels in our data into one of these classifications as follows. If operation $i$ first appears in our data in year $t$, is present in year $t+1$ and $t+2$ but not in year $t+3$, we set its year of entry to $t$ and its year of exit to $t+2$. Note that we do not know the entry year for vessels present in our first data year (2009), nor can we know the exiting year for vessels present in our final data year (2016). The results that follow take this limitation into account.

Table 4 reports descriptive statistics for entrants, exiting vessels, and incumbents across three subperiods: the two years of controlled access regulation, the first two years of IFQs (without permanent quota trades) and the subsequent four-year period of IFQ regulation when permanent quota trades were permitted. The table reports numbers of vessels, subperiod averages for annual revenue (per vessel), vessel value, size economies ($S_n$), the latitude at which the vessel conducted its harvesting operations, and our two cost efficiency measures.

Consider the entrant behavior. We see that, on average, 4.86 vessels entered the groundfish fishery per year. Fifteen new vessels entered the first year of the IFQ program. Comparison with the incumbent vessel class finds that the 2011-12 *entrants* were similarly configured as 2011-12 *incumbents*. Efforts of the Nature Conservancy to promote sablefish harvest with fixed gear may have contributed to the large 2011 entrant class (**?**).

The number of entrants per year drops sharply under the IFQ regulation, to an average of 1.75 per year during 2013-16. In contrast, the average number of vessels exiting under IFQs during the same period is 9.67 per year. Note that 20 vessels exited the groundfish fishery in the first year of the IFQ program; after that, an average of 8.80 vessels per year exited the fishery.

Entering Vessels

| Year | N | Rev. | \$ Vessel | $S_n$ | N. Lat. | $\eta(s,t)$ | $u_i$ |
|---|---|---|---|---|---|---|---|
| 2010† | 6.00 | 226.08 | 83.90 | 6.90 | 38.21 | 0.92 | 1.37 |
| 2011-12 | 10.50 | 636.48 | 50.72 | 6.49 | 40.95 | 0.90 | 1.66 |
| 2013-16 | 1.75 | 1,266.34 | 161.22 | 2.76 | 42.27 | 1.03 | 1.67 |
| All years | 4.86 | 540.95‡ | 118.60 | 4.31 | 41.31 | 0.97 | 1.62 |

Exiting Vessels

| Year | N | Rev. | \$ Vessel | $S_n$ | N. Lat. | $\eta(s,t)$ | $u_i$ |
|---|---|---|---|---|---|---|---|
| 2009-10 | 14.00 | 281.32 | 56.42 | 5.83 | 42.40 | 0.77 | 1.65 |
| 2011-12 | 7.50 | 236.52 | 58.82 | 6.39 | 42.04 | 0.89 | 1.26 |
| 2013-15† | 9.67 | 606.27 | 137.59 | 4.84 | 41.61 | 1.01 | 1.58 |
| All years: | 10.29 | 407.78 | 91.89 | 7.31 | 41.96 | 0.91 | 1.51 |

Incumbent Vessels

| Year | N | Rev. | \$ Vessel | $S_n$ | N. Lat. | $\eta(s,t)$ | $u_i$ |
|---|---|---|---|---|---|---|---|
| 2009-10 | 106.50 | 576.41 | 87.81 | 2.82 | 42.99 | 0.83 | 1.51 |
| 2011-12 | 93.50 | 868.00 | 100.66 | 2.33 | 42.88 | 0.87 | 1.55 |
| 2013-16 | 86.75 | 1,158.12 | 127.35 | 2.51 | 43.16 | 0.92 | 1.58 |
| All years | 93.38 | 923.38 | 110.79 | 2.54 | 43.04 | 0.90 | 1.54 |

Table 4: Entering, Exiting and Incumbent Vessels. Reported values are annual and two-year sub-period averages: N denotes mean number of vessels; Rev. is annual revenue per vessel; \$ Vessel is the vessel capital value in \$ 2016; $S_n$ is economies of size; N. Lat. is the north latitude of the vessels main port; $\eta(s,t)$ denotes common cost efficiency and $u_i$ is the vessel-specific efficiency measure. † There are no observations for entrants in year 2009 or exiting vessels in 2016. ‡ A single outlier observation is dropped from this calculation.

The net effect is a steady decline in the number of incumbent vessels with the exception of 2012 and 2016 where the number of incumbents increased by 5 and 6 boats, respectively.

Next consider differences across vessel categories. Incumbent vessels consistently generated the largest average revenue over the three categories at \$923.38 thousand per year. On average, the annual revenue of entering (exiting) boats is 58.6% (44.2%) of average incumbent revenue. Average revenue of incumbents increased following the switch to IFQ management: by 50.6% during 2011-12 and by another 33.4% during 2013-16. Over time, the revenue generation of entering vessels more closely resembled that of incumbent vessels (39.2% of average annual incumbent revenue in 2009-10, 73.3% in 2011-12, and 109.3% in 2013-16) while exiting vessels generated 48.8% in 2009-10, and 27.2% in 2011-12, and 52.3% in 2013-2016 of incumbent average revenue).

The average value of $S_n$ for entrants, exiting vessels and incumbents, is 4.31, 7.31 and 2.54, respectively. While this difference persists for the boats exiting the fishery under the IFQ program, average size economies for entrants was only 10% larger (2013-16): 2.76 for entrants

| | Model 1 (N=601) | | | | Model 2 (N=601) | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | Estimate | Std. Err. | t-stat. | p-val. | Estimate | Std. Err. | t-stat. | p-val. |
| Con. | −0.337 | 0.338 | −0.997 | 0.319 | −0.395 | 0.330 | −1.196 | 0.232 |
| Vssl. length | −0.004 | 0.009 | −0.405 | 0.686 | −0.004 | 0.009 | −0.422 | 0.673 |
| Returns to size | 0.016 | 0.004 | 4.092 | $< 0.001$ | 0.015 | 0.004 | 3.941 | $< 0.001$ |
| Common eff. $(s,t)$ | 0.244 | 0.136 | 1.800 | 0.072 | 0.246 | 0.133 | 1.850 | 0.065 |
| Vssl. eff. | −0.020 | 0.041 | −0.481 | 0.631 | −0.031 | 0.040 | −0.772 | 0.440 |
| Vssl. eff.$\times I_{t=2010}$ | – | – | – | – | 0.062 | 0.025 | 2.461 | 0.014 |
| Lat., $s$ | 0.007 | 0.005 | 1.365 | 0.173 | 0.007 | 0.005 | 1.352 | 0.177 |
| Date, $t$ | −0.119 | 0.008 | −1.367 | 0.172 | 0.004 | 0.009 | 0.453 | 0.651 |
| Wht. Boat | −0.091 | 0.029 | −3.129 | 0.002 | −0.088 | 0.030 | −2.962 | 0.003 |

Table 5: Exit-Event Linear Probability Model. The dependent variable is an exit event. Standard errors are clustered at the vessel level; there 158 unique vessels.

and 2.51 for incumbents. We see further that exiting vessels are on average smaller than both incumbent and entering vessels. Entering vessels in contrast are 7.05% larger on average than incumbent vessel operations.

The average port latitude for entering vessels is 1.73 degrees southward of the average incumbent port location. The average port location of exiting vessels lies 1.08 degrees southward of the port location for incumbents. This is consistent with our results on common efficiency which suggest the northern latitudes are relatively more productive than southern latitudes.

Lastly, Table 4 reports average efficiency scores, $u_i$, across the three vessel classes. Averaging over all data years finds that entering vessels are *in*efficiency relative to incumbents, average values are 1.66 versus 1.55. Exiting vessels are more cost-efficient than incumbents and entrants although the differences are small. The average cost-efficiency of exiting vessels ($u_i$) was 23.3% lower than incumbent and entering vessels during the first two years of the IFQ program, with this gap shrinking in later years. Comparison of vessel-group average efficiency scores is inconclusive.

## 5.3 Vessel exit

This section presents results from a linear probability model of the decision to exit the IFQ fishery. We construct an indicator variable for vessel operation $i$ in year $t$ that is equal to 1 if the vessel exited the groundfish fishery, and 0 otherwise. This indicator is regressed on vessel characteristics, measured economies of size, our estimate of common productivity, and vessel-specific efficiency measures. Note that we cannot identify exit events that occur after 2016. Moreover, to focus the analysis on the IFQ-regime forces affecting vessel exit decisions, we drop 2009 data. The data used in this analysis include 601 vessel-year observations with 64 exit events (an exit rate of 10.09%).

Results from two regression models are reported in Table 5. Both models include spatial and temporal measures to control for unobserved influences on exit patterns, and a dummy variable for whiting specialists vessels which exited less frequently than vessels specializing in groundfish.

Both models find that economies of size is positively and statistically significantly correlated with exit events, suggesting that vessel operations that did not exploit available economies of size were more likely to exit under IFQs. The results find that common cost efficiency is positively correlated with exit events, i.e., vessels operating in unproductive regions were more likely to exit.

Interestingly, our models do not find evidence that vessel size alone or vessel-level cost inefficiency are strongly correlated with exit. Both models indicate that technical efficiency has a negative effect on exit; in both cases the parameter is statically insignificant at conventional levels. Model 2 allows the effect of vessel-specific cost inefficiency to be different during the first year of the IFQ program. Model 2 finds that $u_i$ is positively and significantly correlated with exit events, with p-value, 0.014.

Summarizing, the exit event model suggests vessels that did not exploit available economies of size were more likely to exit the groundfish fishery under the IFQ regulation. The correlation between vessel-specific technical efficiency and exit is positive in the first year of the IFQ program but weakly negative thereafter. We therefore cannot conclude that technical efficiency is a reliable predictor of exit patterns.

## 6 Conclusion

This paper evaluates changes in harvesting efficiency, capital investment/divestment incentives, vessel exit patterns, and resource rent in a major US fishery that switched from input control regulations to an individual fishing quotas. We evaluate these effects using data on the universe of vessels that operated in the groundfish fishery over an eight year period that spans regulatory reform. We modify a time-varying stochastic cost frontier model (Battese and Coelli, 1988; Kumbhakar, 1990) to control for temporal and spatial effects of unobserved stock abundance and/or other unknown factors that may confound efficiency during the data period. The methodology isolates changes in efficiency that are attributable to the individual fishing quota regulation.

Our results find that input-controls slowed the dissipation of resource rent in the West Coast groundfish trawl fishery. During the first six years of IFQs, the number of active groundfish vessels declined 5.77% per year and fishery rent increased by 6.02% per year. The cost per harvested pound of groundfish initially increased before it stabilized under IFQs. Evidence suggests that removal of redundant capital built up under the input control regime, economies of size as quota was consolidated onto fewer vessels, and increases in total harvests of the groundfish fleet were key sources of rent gains. Results find further that vessels that did not exploit available economies in harvesting exited the fishery. Vessels fishing in relatively unproductive regions of the fishery were also more likely to exit. Finally, while technically inefficient vessels were more likely to exit in the first year of the quota regulation, evidence of technical inefficiency among vessels that exited in subsequent years is not indicated.

Overall, we find that fleet rationalization and rent generation in the West Coast groundfish trawl IFQ program followed theoretical predictions: fleet size declined to align harvesting capacity with the aggregate groundfish quotas. Resource rent substantially increased under IFQs with estimates at \$31.26 million per year (40.48% of revenue) per in the final years of our data, 2015-16. Importantly, evidence from our structural empirical model suggests that fleet restructuring remains incomplete six years following implementation of the IFQ regulation. Thus the full economic benefits of the IFQ program are yet realized (Weninger, 1998; Grafton et al., 2000; Turner and Weninger, 2005; Munro et al., 2009).

With the exception of the first year of the IFQ regulation, vessels that exited the groundfish fishery exhibited technically efficiency that is comparable with those that remained active. Multiple factors likely influence the decision to exit an IFQ fishery. Further research into the determinants of capital divestment decisions, the timing of exit, and the implications for harvesting efficiency may yield new insights and perhaps policy guidance to facilitate the transition to the IFQ-regime fleet structure.

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# A Appendix

## A.1 Data descriptive statistics

The analysis of landings, cost, and revenue data offer a coarse overview of economic performance before and after the introduction of the catch shares management program. Table 6 reports descriptive statistics for our data separated into four two-year subperiods (parts A-D), and for the full sample. The results show that average costs, revenues and net revenues increased considerably in the post-catch shares period. In 2009-10, sample average net revenue increased from \$112,851 to \$182,476 (61.7%). The cause(s) of the net revenue increase are not fully known. Average annual landings per vessel increased 8.9%, over 200,000 pounds per year. Days at sea, on the other hand, fell by almost 9 (9.05%). One contribution to the net-revenue increase under catch shares management is the increase in dockside prices; the average landings-weighted fish price increased from \$0.65 in 2009-10 to \$1.20 per pound in 2011-12, an increase of (89.2%). Price increases have been observed in other fisheries that switch from command and control management to rights-based management approaches. An important reason is that shortened fishing seasons under command and control regulations, which are often subject to periodic fishery closures, can create market gluts and low dockside prices (Casey et al. (1995); Weninger and Waters (2003)). Higher per-vessel net revenues under catch shares management may however be the result of exogenous price changes. Further investigation of the underlying cause of the price increase in the West Coast groundfish fishery is therefore warranted.

Table 7 reports sample average (i) landings shares, (ii) revenue shares, and (iii) dockside prices. Part A of the table reports values for the pre-catch share period, 2009-10; parts B-D reports values for the catch shares management period, 2011-16. Results show that Pacific whiting, dover sole, non-DTS species, and shrimp make up the largest share of annual landings by weight. This is true for both the pre- and the post-catch shares periods. Annual average landings shares have remained relatively stable across the two management regimes. Pacific whiting, trawl-caught sablefish, dover sole, and thornyhead landings shares have fallen slightly while shares of other species, pot-caught sablefish, crab, and shrimp have risen. Evidence presented below shows that crab and shrimp tend to be harvested independently of other groundfish species. The increase in their shares in total landings may reflect an increase in specialization in the harvest of these species.

The share of pot-caught sablefish landings, while small relative to total landings, has increased substantially during the first two years of the catch shares management program. The regulatory change that allows different gear types under the catch shares program is likely responsible for this change in gear usage. The cost and net revenue analysis below supports the shift to pot-caught sablefish fishing (Table 7).

| | A. 2009-10 ($N$ = 244) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Land. | DAS | Var. Cost | Fixed Cost | Cap. Cost | Revenue | Fuel Cost Shr. | Labor Cost Shr. |
| Average | 2,114.27 | 95.32 | 292.61 | 32.31 | 76.83 | 517.61 | 0.24 | 0.68 |
| Std. Dev. | 3,016.61 | 50.66 | 160.60 | 20.12 | 124.15 | 336.90 | 0.11 | 0.11 |
| [10,90]'th % | [214.45, 5,996.71] | [35.60, 149.60] | [98.57, 486.19] | [5.89, 57.95] | [14.87, 189.58] | [149.70, 895.75] | [0.12, 0.38] | [0.56, 0.80] |
| | B. 2011-12 ($N$ = 219) | | | | | | | |
| | Land. | DAS | Var. Cost | Fixed Cost | Cap. Cost | Revenue | Fuel Cost Shr. | Labor Cost Shr. |
| Average | 2,964.84 | 88.94 | 444.62 | 38.29 | 86.21 | 799.04 | 0.23 | 0.69 |
| Std. Dev. | 4,064.99 | 40.54 | 298.17 | 26.38 | 144.85 | 574.44 | 0.09 | 0.11 |
| [10,90]'th % | [117.00, 10,206.38] | [29.9, 134.00] | [111.54, 834.45] | [7.64, 69.40] | [16.39, 136.64] | [136.64,1,543.92] | [0.12, 0.34] | [0.56, 0.81] |
| | C. 2013-14 ($N$ = 203) | | | | | | | |
| | Land. | DAS | Var. Cost | Fixed Cost | Cap. Cost | Revenue | Fuel Cost Shr. | Labor Cost Shr. |
| Average | 3,998.46 | 91.81 | 524.79 | 45.36 | 103.97 | 986.32 | 0.21 | 0.72 |
| Std. Dev. | 5,859.72 | 40.73 | 324.64 | 31.29 | 142.60 | 640.29 | 0.09 | 0.11 |
| [10,90]'th % | [136.06, 13,367.70] | [37.30, 145.70] | [121.59, 977.94] | [11.40, 81.93] | [23.86, 237.34] | [185.97,1,849.53] | [0.10, 0.32] | [0.57, 0.82] |
| | D. 2015-16 ($N$ = 178) | | | | | | | |
| | Land. | DAS | Var. Cost | Fixed Cost | Cap. Cost | Revenue | Fuel Cost Shr. | Labor Cost Shr. |
| Average | 4,920.97 | 89.44 | 616.93 | 46.44 | 130.90 | 1,253.17 | 0.14 | 0.79 |
| Std. Dev. | 7,974.36 | 42.99 | 402.75 | 29.08 | 161.77 | 873.30 | 0.10 | 0.12 |
| [10,90]'th % | [204.43, 14,947.19] | [26.00, 143.00] | [149.83, 1,215.94] | [12.24, 81.18] | [34.44, 298.75] | [220.59, 2,603.98] | [0.04, 0.29] | [0.63, 0.91] |
| | All Years ($N$ = 844) | | | | | | | |
| | Land. | DAS | Var. Cost | Fixed Cost | Cap. Cost | Revenue | Fuel Cost Shr. | Labor Cost Shr. |
| Average | 3,380.10 | 91.58 | 456.30 | 39.98 | 97.20 | 854.17 | 0.21 | 0.72 |
| Std. Dev. | 5,548.73 | 44.24 | 322.65 | 27.25 | 143.66 | 668.39 | 0.11 | 0.12 |
| [10,90]'th % | [153.04, 10,400.64] | [34.40, 145.00] | [112.02, 902.58] | [8.75, 74.59] | [19.36, 226.44] | [159.40, 1,723.79] | [0.08, 0.35] | [0.57, 0.85] |

Table 6: Descriptive Statistics: Landings are in thousands of pounds; DAS indicates days at sea per year; variable, fixed and capital costs and revenue are reported in thousands of 2016 dollars.

A. 2009-10

| | Whiting | Sblf. Trwl. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| Land. Shr. | 0.28 | 0.05 | 0.23 | 0.05 | 0.19 | 0.03 | 0.06 | 0.10 | 0.01 |
| Rev. Shr. | 0.21 | 0.19 | 0.14 | 0.04 | 0.14 | 0.04 | 0.15 | 0.07 | 0.01 |
| Price | 0.06 | 2.06 | 0.35 | 0.52 | 0.46 | 1.11 | 2.05 | 0.49 | 2.61 |

B. 2011-12

| | Whiting | Sblf. Trwl. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| Land. Shr. | 0.25 | 0.03 | 0.15 | 0.03 | 0.15 | 0.07 | 0.09 | 0.15 | 0.08 |
| Rev. Shr. | 0.22 | 0.10 | 0.10 | 0.03 | 0.12 | 0.07 | 0.16 | 0.11 | 0.09 |
| Price | 0.07 | 2.21 | 0.43 | 0.56 | 0.64 | 1.07 | 2.98 | 0.61 | 2.91 |

C. 2013-14

| | Whiting | Sblf. Trwl. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| Land. Shr. | 0.28 | 0.03 | 0.12 | 0.04 | 0.16 | 0.05 | 0.10 | 0.18 | 0.04 |
| Rev. Shr. | 0.24 | 0.06 | 0.08 | 0.03 | 0.15 | 0.05 | 0.19 | 0.15 | 0.04 |
| Price | 0.07 | 1.61 | 0.45 | 0.56 | 0.64 | 1.03 | 3.19 | 0.53 | 2.81 |

D. 2015-16

| | Whiting | Sblf. Trwl. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| Land. Shr. | 0.27 | 0.03 | 0.13 | 0.03 | 0.18 | 0.05 | 0.06 | 0.17 | 0.08 |
| Rev. Shr. | 0.22 | 0.08 | 0.08 | 0.03 | 0.18 | 0.06 | 0.12 | 0.16 | 0.08 |
| Price | 0.04 | 1.75 | 0.43 | 0.58 | 0.63 | 1.01 | 4.08 | 0.73 | 3.08 |

All Years

| | Whiting | Sblf. Trwl. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| Land. Shr. | 0.27 | 0.04 | 0.16 | 0.04 | 0.17 | 0.05 | 0.08 | 0.14 | 0.05 |
| Rev. Shr. | 0.21 | 0.11 | 0.10 | 0.03 | 0.15 | 0.05 | 0.16 | 0.12 | 0.05 |
| Price | 0.06 | 1.93 | 0.41 | 0.55 | 0.59 | 1.06 | 3.01 | 0.58 | 2.90 |

Table 7: Landings, Revenue and Prices 2009-16. SblfTrwl is trawl-caught sablefish; Thnyhead is short- and longspine thornyheads; non-DTS includes all groundfish species, excluding whiting, dover sole, thornyheads and sablefish; Other Sp. includes non-groundfish species such as pelagic and highly migratory species and salmon; SblfPot is pot-caught sablefish.

Sample average revenue shares for sablefish and crab are the largest due to the higher prices paid at the dock for these species. Changes in revenue shares across the two data periods follow the pattern seen with landings shares, although shrimp revenues shares are unchanged. Results in Table 7 reveal that average dockside prices for all species groups increased in the first two years of the catch shares management program.

## A.2 Cost structure

Likelihood ratio tests are used to evaluate alternative specifications of our cost technology (equation (5)). We test for second-order effects in input prices, second-order and cross-species effects,

|  | Whit. a.s. | Sblf. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| Whit. s.s. | 0.410 | -0.153 | -0.178 | -0.178 | 0.090 | 0.218 | -0.058 | -0.171 | -0.088 |
| Whit. a.s. | 1.000 | -0.261 | -0.258 | -0.226 | -0.164 | 0.041 | -0.152 | -0.172 | -0.078 |
| Sblf. | - | 1.000 | 0.813 | 0.798 | 0.495 | 0.053 | 0.085 | 0.173 | -0.153 |
| D. Sole | - | - | 1.000 | 0.677 | 0.614 | 0.071 | 0.032 | 0.152 | -0.154 |
| T.Heads | - | - | - | 1.000 | 0.277 | -0.047 | 0.072 | 0.120 | -0.137 |
| Non-DTS | - | - | - | - | 1.000 | 0.319 | -0.034 | -0.060 | -0.146 |
| Other Sp. | - | - | - | - | - | 1.000 | -0.087 | -0.171 | -0.031 |
| Crab | - | - | - | - | - | - | 1.000 | 0.051 | 0.312 |
| Shrimp | - | - | - | - | - | - | - | 1.000 | -0.081 |

Table 8: Annual Landings: Simple correlations.

| Whit. s.s. | Whit. a.s. | Sblf. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| 1.356 | 1.333 | 4.690 | 3.910 | 3.076 | 2.112 | 1.202 | 1.159 | 1.134 | 1.184 |

Table 9: Variance Inflation Factors.

and input price-species cross-effects. Table 1 (Section 5) summarizes results from these tests.

First, the null hypothesis that second-order fuel price and capital effects are jointly zero ($H_0 : \beta_{ww} = \beta_{kk} = 0$) cannot be rejected at conventional levels of significance (p-value = 0.381). Based on this result, second-order price and capital effects were dropped from our specification.

Next, we test the restriction that the cost technology is log-linear in harvests, i.e., $H_0 : \beta_{h_{mm}} = 0$, for $m = 1,\ldots,M$; this restriction is rejected (p-value < 0.001). Similarly, we test the restriction that individual groundfish species cross-effects can be dropped from the model, $H_0 : \beta_{mn} = 0$, for all$m,n \in M, m \neq n$. The chi-square statistic for this test is 34.918 with p-value 0.005. This finding is consistent with our assertion that the groundfish trawl technology is joint-in-inputs across major groundfish trawl species.

The null hypothesis that fuel price and landings effects are zero, i.e., $H_0 : \beta_{wm} = 0$, for $m = 1,\ldots,M$ is also rejected (p-value < 0.001). However, based on anecdotal evidence that whiting fishing is relatively fuel-intensive, we consider a specification with fuel price-landings effects set to zero for all species other than whiting ($H_0 : \beta_{wm} = 0$, for all $m \neq$ whiting). We fail to reject this restriction (p-value=0.124). We therefore set $\beta_{wm} = 0$ for all non-whiting species or species groups. Next, the hypothesis that capital-landings effects are zero ($H_0 : \beta_{km} = 0$, for $m = 1,\ldots,M$) is rejected at conventional levels of significance (p-value < 0.001). Note, the parameter estimates reflecting capital-landings cross effects $\beta_{km}$ are negative, suggesting that cost-capital elasticity is declining in landings quantity (see Table 10).[26]

Next, we test some potential aggregations of species. The null hypothesis that at-sea and shore-based whiting landings have distinct effects on groundfish landings costs is tested against

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[26] Asymptotic normal tests of individual parameter restrictions fail to reject the null hypotheses that $\beta_{km} = 0$ for trawl-caught sablefish, dover sole, thornyheads, and shrimp.

the alternative hypothesis that the two whiting types can be linearly aggregated. We fail to reject the implied parameter restriction (p-value = 0.387). We therefore aggregate at-sea and shoreside whiting landings linearly.

Finally, trip-level correlations in Table (12) suggest that dover sole, thornyheads, and sablefish (known as the DTS group among industry and managers) are grouped together perhaps due to the frequency with which they are jointly harvested. We however test and reject a specification in which DTS are linearly aggregated (p-value < 0.001)

Summarizing, our preferred specification for the multi-species cost technology (equation (5)) includes first-order effects for fuel price and capital input, first- and second-order effects for nine landed species (whiting, trawl-caught sablefish, dover sole, thornyheads, non-DTS species, all other groundfish species, crab, shrimp and pot-caught sablefish), cross-effects for all groundfish species, a fuel price-landings cross-effect for whiting, and capital-landings cross-effects for all species.

### A.2.1 Cost model parameter estimates

Table 10 contains the parameter results from maximum likelihood estimation of the multi-species stochastic cost frontier model.

| | Preferred Model | | | | No Cross-Species Effects | | | |
|---|---|---|---|---|---|---|---|---|
| Parm. | Est. | Std. Err. | t-stat. | p-val. | Est. | Std. Err. | t-stat. | p-val. |
| $\beta_0$ | 6.661 | 0.191 | 34.820 | <0.001 | 6.841 | 0.186 | 36.761 | <0.001 |
| $\beta_1$ | 0.144 | 0.041 | 3.552 | <0.001 | 0.161 | 0.040 | 3.976 | <0.001 |
| $\beta_2$ | 12.994 | 6.692 | 1.942 | 0.052 | 15.760 | 6.524 | 2.416 | 0.016 |
| $\beta_3$ | 2.358 | 1.434 | 1.644 | 0.100 | 2.623 | 1.285 | 2.040 | 0.041 |
| $\beta_4$ | 6.287 | 6.472 | 0.971 | 0.331 | 8.095 | 6.458 | 1.253 | 0.210 |
| $\beta_5$ | 3.296 | 0.937 | 3.518 | <0.001 | 2.756 | 0.744 | 3.704 | < 0.001 |
| $\beta_6$ | 20.689 | 2.047 | 10.106 | <0.001 | 15.082 | 1.696 | 8.892 | < 0.001 |
| $\beta_7$ | 19.835 | 1.730 | 11.465 | <0.001 | 18.706 | 1.770 | 10.571 | < 0.001 |
| $\beta_8$ | 2.194 | 0.472 | 4.653 | <0.001 | 2.115 | 0.487 | 4.421 | <0.001 |
| $\beta_9$ | 18.995 | 1.925 | 9.870 | <0.001 | 18.752 | 1.989 | 9.427 | < 0.001 |
| $\beta_{11}$ | -0.003 | 0.001 | -4.740 | <0.001 | -0.001 | <0.001 | -2.444 | 0.015 |
| $\beta_{12}$ | 0.074 | 0.166 | 0.447 | 0.655 | - | - | - | - |
| $\beta_{13}$ | -0.008 | 0.031 | -0.262 | 0.794 | - | - | - | - |
| $\beta_{14}$ | -0.594 | 0.316 | -1.881 | 0.060 | - | - | - | - |
| $\beta_{15}$ | -0.002 | 0.013 | -0.147 | 0.883 | - | - | - | - |
| $\beta_{16}$ | 0.261 | 0.053 | 4.940 | <0.001 | - | - | - | - |
| $\beta_{22}$ | -15.033 | 14.294 | -1.052 | 0.293 | -10.676 | 6.775 | -1.576 | 0.115 |
| $\beta_{23}$ | -1.978 | 2.124 | -0.931 | 0.352 | - | - | - | - |
| $\beta_{24}$ | 6.211 | 5.800 | 1.071 | 0.284 | - | - | - | - |
| $\beta_{25}$ | 0.836 | 1.146 | 0.730 | 0.466 | - | - | - | - |
| $\beta_{26}$ | 17.482 | 9.847 | 1.775 | 0.076 | - | - | - | - |
| $\beta_{33}$ | -0.181 | 0.425 | -0.139 | 0.670 | 0.040 | 0.129 | 0.309 | 0.758 |
| $\beta_{34}$ | 2.273 | 1.524 | 0.405 | 0.134 | - | - | - | - |
| $\beta_{35}$ | -0.135 | 0.261 | 0.174 | 0.606 | - | - | - | - |
| $\beta_{36}$ | -0.545 | 1.589 | -0.502 | 0.733 | - | - | - | - |
| $\beta_{44}$ | -8.820 | 5.354 | -0.836 | 0.100 | 0.691 | 3.707 | 0.187 | 0.852 |
| $\beta_{45}$ | -1.603 | 1.405 | -0.392 | 0.254 | - | - | - | - |
| $\beta_{46}$ | -13.891 | 10.227 | -0.018 | 0.174 | - | - | - | - |
| $\beta_{55}$ | -0.270 | 0.205 | -1.244 | 0.188 | -0.491 | 0.137 | -3.577 | <0.001 |
| $\beta_{56}$ | -0.409 | 0.842 | 0.518 | 0.627 | - | - | - | - |
| $\beta_{66}$ | 2.485 | 3.632 | -0.494 | 0.494 | -2.903 | 3.052 | -0.951 | 0.342 |
| $\beta_{77}$ | -3.649 | 2.283 | -1.221 | 0.110 | -3.886 | 2.340 | -1.661 | 0.097 |
| $\beta_{88}$ | -0.105 | 0.086 | -0.918 | 0.219 | -0.149 | 0.085 | -1.754 | 0.079 |
| $\beta_{99}$ | -12.872 | 1.444 | -6.506 | <0.001 | -12.895 | 1.479 | -8.716 | <0.001 |
| $\beta_{w1}$ | 0.032 | 0.006 | 3.408 | <0.001 | 0.028 | 0.006 | 4.348 | <0.001 |
| $\beta_{k1}$ | -0.008 | 0.003 | -3.596 | 0.019 | -0.010 | 0.003 | -2.984 | 0.003 |
| $\beta_{k2}$ | -0.959 | 0.684 | -0.676 | 0.161 | -1.194 | 0.666 | -1.791 | 0.073 |
| $\beta_{k3}$ | -0.181 | 0.146 | -0.814 | 0.215 | -0.233 | 0.128 | -1.826 | 0.068 |
| $\beta_{k4}$ | -0.461 | 0.666 | -0.438 | 0.489 | -0.695 | 0.666 | -1.043 | 0.297 |
| $\beta_{k5}$ | -0.222 | 0.093 | -2.655 | 0.017 | -0.177 | 0.073 | -2.414 | 0.016 |
| $\beta_{k6}$ | -1.917 | 0.221 | -6.842 | <0.001 | -1.221 | 0.163 | -7.513 | <0.001 |
| $\beta_{k7}$ | -1.661 | 0.171 | -8.785 | <0.001 | -1.534 | 0.175 | -8.780 | <0.001 |
| $\beta_{k8}$ | -0.143 | 0.048 | -1.601 | 0.003 | -0.132 | 0.049 | -2.677 | 0.007 |
| $\beta_{k9}$ | -1.376 | 0.188 | -5.912 | <0.001 | -1.350 | 0.194 | -6.949 | <0.001 |
| $\beta_w$ | 0.454 | 0.046 | 6.631 | <0.001 | 0.440 | 0.047 | 9.328 | <0.001 |
| $\beta_k$ | 0.426 | 0.018 | 33.049 | <0.001 | 0.413 | 0.018 | 23.544 | <0.001 |
| $\alpha_s$ | -0.489 | 0.190 | -2.578 | 0.001 | -0.464 | 0.198 | -2.339 | 0.019 |
| $\alpha_t$ | 0.484 | 0.163 | 2.960 | 0.003 | 0.576 | 0.189 | 3.049 | 0.002 |
| $\alpha_{st}$ | 0.118 | 0.312 | 0.377 | 0.706 | 0.052 | 0.370 | 0.140 | 0.887 |
| $\sigma_v$ | 0.190 | 0.001 | 177.492 | <0.001 | 0.199 | 0.001 | 173.719 | <0.001 |
| $\sigma_u$ | 0.496 | 0.030 | 16.756 | <0.001 | 0.447 | 0.024 | 18.891 | <0.001 |

Table 10: MLE Parameter Estimates: p-values are for a two-sided test of the null hypothesis that the estimated parameter is equal to zero.

## A.3 Additional results

### A.3.1 Species-specific rent

A. Pre-Catch Shares Period 2009-10

| | Whit. | Sblf. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| $y_i$ | 3,964.77 | 52.58 | 218.47 | 50.30 | 145.91 | 13.23 | 72.77 | 370.87 | 44.09 |
| $p_i$ | 0.06 | 2.06 | 0.35 | 0.52 | 0.46 | 1.11 | 2.05 | 0.49 | 2.61 |
| $C_i(.)$ | 0.03 | 0.69 | 0.10 | 0.33 | 0.27 | 0.60 | 0.81 | 0.22 | 1.06 |
| $p_i - C_i(.)$ | 0.04 | 1.31 | 0.24 | 0.18 | 0.17 | 0.51 | 0.82 | 0.22 | 1.55 |

B. IFQ Period 2011-12

| | Whit. | Sblf. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| $y_i$ | 3,780.35 | 40.87 | 204.92 | 44.68 | 153.00 | 21.53 | 62.29 | 582.47 | 90.28 |
| $p_i$ | 0.07 | 2.21 | 0.43 | 0.56 | 0.64 | 1.07 | 2.98 | 0.61 | 2.91 |
| $C_i(.)$ | 0.04 | 1.13 | 0.14 | 0.43 | 0.42 | 0.83 | 1.21 | 0.35 | 2.05 |
| $p_i - C_i(.)$ | 0.01 | 0.99 | 0.26 | 0.10 | 0.20 | 0.23 | 1.01 | 0.19 | 0.85 |

C. IFQ Period 2013-16

| | Whit. | Sblf. | D. Sole | T. Heads | Non-DTS | Other Sp. | Crab | Shrimp | Sblf. Pot |
|---|---|---|---|---|---|---|---|---|---|
| $y_i$ | 5,347.60 | 46.71 | 264.54 | 53.76 | 249.15 | 32.05 | 90.54 | 846.53 | 175.65 |
| $p_i$ | 0.06 | 1.68 | 0.44 | 0.57 | 0.64 | 1.02 | 3.59 | 0.63 | 2.96 |
| $C_i(.)$ | 0.05 | 1.26 | 0.14 | 0.43 | 0.55 | 0.96 | 1.65 | 0.45 | 3.87 |
| $p_i - C_i(.)$ | -0.01 | 0.26 | 0.24 | 0.10 | 0.05 | 0.06 | 1.36 | 0.14 | -0.92 |

Table 11: Landings, Price, Marginal Cost, and Marginal Profit. Landings $y_i$ are the average thousands of pounds per year; Costs and profit are median values in 2016 dollars. Sblf. is trawl-caught sablefish; D. Sole is dover sole; T. Heads is short- and longspine thornyheads; Non-DTS includes all groundfish species excluding dover sole, thornyheads and sablefish; Other Sp. includes pelagic and highly migratory species, salmon, and halibut; Sblf. Pot is pot-caught sablefish.

Table 11 illustrates additional changes in groundfish rent generation during the 2009-16 data period. The table reports sample average landings (thousands of pounds), the median prices, marginal costs, and marginal profits for the nine species we consider. Part A of the table reports results for the pre-IFQ data; parts B and C report results for the first two years and the following four years of IFQ regulation, in order.

## A.4 Annualized capital expenditures

We follow the view that vessel capital is a quasi-fixed factor of production but adjust capital services for the quantity of services allocated during each production period (Kirkley and Strand, 1988; Segerson and Squires, 1990). To this end, we first measure heterogeneity in capital services for vessels in our data using a hedonic model of self-reported vessel values. We assume sale values reflect the present value of the flow of capital services that a vessel configuration can provide. Our data contain 278 unique observations of self-reported vessel values. We regress

GDP-deflated vessel values on vessel length (entered quadratically), engine horse power, vessel fuel capacity, cross-effect terms, and a quadratic time trend to control for time-varying unobserved elements that effect vessel values.[27] We use the fitted model to predict the value of each vessel in our data in USD 2016.

We multiply these fitted values by an annual capital rental rate of 7% to obtain an estimate of annual available capital in unit of dollars.[28] Finally, we adjust the annual capital cost by the proportion of the year the vessel capital was employed in the groundfish fishery; the reported days at sea fishing for all landed species in our data divided by the maximum days at sea. We denote this estimate as $k_i$ for vessel operation $i$.

## A.5 Multispecies groundfish technology

We assume the groundfish harvest technology is joint-in-inputs.[29] We assume further that groundfish fishermen organize factor inputs to minimize the cost of landing an exogenously determined quantities in groundfish and non-groundfish species. This assumption is motivated by two institutional realities. First, the regulations under which groundfish fishermen operate are designed to limit fishing mortality and address long term stock conservation goals. The controlled access regime, for example, capped bi-monthly harvests of individual groundfish species. The IFQ regulation caps annual harvest of individual species.

A second institutional feature of the West Coast groundfish trawl fishery is strong vertical coordination between harvesting and processing firms. Vessel skippers indicate that processors closely monitor downstream demand for the final consumable products and hire sufficient labor to ensure sufficient processing capacity to handle influxes of the highly perishable catch. Processing firms control the quantities of individual species and the timing of deliveries to ensure available processing capacity is utilized efficiently.

Jointness-in-inputs is a plausible property of the groundfish technology. Cost complementarity can arises in the presence of public factors of production, i.e., multiple groundfish species co-habitate in common marine environments and are captured together by trawl nets. An analysis of trip-level landings confirms that there are species groups that are consistently landed together on fishing trips and other species that are consistently absent. We maintain that the cost of harvesting species that are landed together at the trip level are separable from the costs

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[27] The R-square statistic for this model is 0.811.

[28] A 7% financial capital cost is recommended by the US Office of Management and Budget as an average rate of return on private investments (see https://www.whitehouse.gov/omb/).

[29] Scope economies arise in multi-species commercial fisheries due to the presence of public factors of production. Multiple groundfish species are regularly intercepted when trawl gear is dragged through the water column. Multiple species may also be trapped as bycatch by fixed gear. Our data include annual expenditures on factors of production. We do not identify species-specific factor allocations.

| Trips landing sp. | Whit. (s.s.) | Whit. (a.s.) | Sblf. | D. Sole | T. Heads | Non-DTS | Other | Crab | Shrimp | Sblf. (Pot) |
|---|---|---|---|---|---|---|---|---|---|---|
| Whit. (s.s.) | - | 0.000 | 0.412 | 0.293 | 0.410 | 0.988 | 0.887 | 0.042 | 0.001 | 0.000 |
| Whit. (a.s.) | 0.000 | - | 0.091 | 0.018 | 0.055 | 0.458 | 0.491 | 0.000 | 0.001 | 0.000 |
| Sblf. | 0.289 | 0.030 | - | 0.853 | 0.863 | 0.975 | 0.530 | 0.027 | 0.001 | 0.000 |
| D. Sole | 0.228 | 0.007 | 0.942 | - | 0.879 | 0.988 | 0.478 | 0.029 | 0.001 | 0.000 |
| T. Heads | 0.310 | 0.019 | 0.926 | 0.854 | - | 0.979 | 0.529 | 0.022 | 0.001 | 0.000 |
| Non DTS | 0.397 | 0.085 | 0.558 | 0.512 | 0.522 | - | 0.650 | 0.022 | 0.002 | 0.030 |
| Other | 0.493 | 0.126 | 0.419 | 0.342 | 0.389 | 0.898 | - | 0.030 | 0.003 | 0.004 |
| Crab | 0.069 | 0.000 | 0.065 | 0.061 | 0.049 | 0.090 | 0.091 | - | 0.000 | 0.004 |
| Shrimp | 0.003 | 0.008 | 0.004 | 0.002 | 0.003 | 0.013 | 0.013 | 0.012 | - | 0.001 |
| Sblf. (Pot) | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.522 | 0.054 | 0.016 | 0.004 | - |
| Trips w/$h_i > 0$ | 8,087 | 3,741 | 11,509 | 10,413 | 10,717 | 20,105 | 14,564 | 4,866 | 3,671 | 1,152 |
| Prop. w/$h_i > 0$ | 0.255 | 0.118 | 0.362 | 0.328 | 0.337 | 0.633 | 0.458 | 0.153 | 0.116 | 0.036 |

Table 12: Proportion of trips landing row species that also land column species.

of jointly harvested species.[30]

Correlations across harvested species are reported in Table 12. Results reveal important properties of the groundfish technology and industry organization. First, consistent with regulatory constraints, vessels that harvest whiting land their catch either at sea or on shore, but not both (trip-level correlation between at-sea and shore-side whiting harvest is zero). Groundfish fishermen do land whiting both at-sea to motherships and at shore-based processors during a given year (see annual harvests correlations in Table 8 in Appendix A.1).

Next, gear switching occurs between but not within trips; vessels are prohibited from using or even carrying multiple gear types on a single trip. The correlations between pot caught sablefish and other trawl species are all zero. We see further that crab and shrimp fishing is conducted independently of trawl fishing; trip-level correlations between crab, shrimp and all other groundfish species are essentially zero.

Correlations across trawl-caught groundfish species including whiting, sablefish, dover sole, thornyheads, and the non-DTS group are the range of 0.228-0.988. These species are harvested jointly at the trip- and therefore at the seasonal levels. Harvest correlations are less than unity and are not uniform across species. From the results in Table 12, we conclude that the assumption of fixed output proportions for major trawl species is not supported by our data.

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[30] An alternative but separate source of jointness arises in the presence of a fixed but allocatable factor of production (Shumway et al., 1988). Our data indicate that most vessel operations spend far fewer days at sea than is physically possible. It is unlikely these vessel operators face constraints on the available capital services. Jointness due to the presence of a fixed but allocatable capital input is not considered further in this study.