1 Introduction

The severely depleted Gulf of Mexico reef-fish fishery, the focus of this paper, saw the introduction of limited entry regulation with common-pool fishing quotas (CFQs) in 1990 to keep the annual catch within a set total allowable catch (TAC). This command-and-control approach to fisheries management led to unintended consequences, notably fishers engaging in derby fishing, that is, braving poor weather conditions to beat the competition and the clock, and investing into greater strike capacity. In addition, market gluts led to price volatility with a significant drop in dockside prices during the increasingly narrow open season.

In response, the Gulf of Mexico Fishery Management Council (Gulf Council) replaced seasonal closures with individual, tradable fishing quotas (ITQs or IFQs) programs, first for red snapper in 2007 and then for an additional set of reef fish species collectively referred to as grouper-tilefish in 2010. The policy's stated primary objectives were to mitigate derby-fishing conditions, stabilize prices, and reduce overcapacity. IFQs were expected to have a consolidating effect on fleet size, since the contest for access to fish would no longer occur at sea, but in the marketplace.

Of course, the standard prediction of an IFQ-induced fleet size reduction is *ceteris paribus*. In reality, qualitative policy changes did not occur in isolation: the fishing industry has simultaneously been affected by quantitative changes, such as in the TAC, prices for both inputs and outputs, and biomass. The purpose of this paper is to explore the roles of these factors through the lens of a simple bioeconomic model. We find that these concurrent changes were significant in magnitude, amplifying the consolidating effect of tradable catch shares.

Intuitively, the price of an allocation (the rental price for the right to catch one pound of fish) adds to the cost of fishing and reduces operating margins. Since fishing privileges (because harvesting privileges are revocable without compensation, we cannot speak of fishing rights *per se*) are tradable, owners of marginal vessels would find it profitable to sell or lease their privileges to more cost-efficient producers and exit the industry. The conventional wisdom, then, has been that regulatory failure during the 1990-2007 CFQ period led to overcapacity, while its alleviation in the form of IFQs would help restore industry efficiency.

Notwithstanding Felthoven *et al.*'s (2009) argument that fleet capacity in multi-species fisheries is likely to be overestimated, Solís *et al.* (2014a and 2014b) estimate "that about 75 vessels (or about one-fifth of the 2011 fleet) could have harvested the 2011 quota" (2014b, p.16). While they argue that IFQs in the Gulf of Mexico improved technical efficiency (2014a, p.75), they note that the remaining fleets "have not yet found their economically optimal configuration despite their ability to purchase and/or lease quota" (2014a, p.82). Since Clark *et al.* (1979), several studies have concluded that the impact of IFQ programs in multi-species fisheries is likely to be slow. Nevertheless, National Marine Fisheries Service (NMFS) data from the Southeast Coastal Fisheries Logbook Program, shown in Figure 1, indicate that the size of the Gulf of Mexico reef-fish fishery's active fleet has remained flat since the 2010 introduction of the grouper-tilefish IFQ, even as recovering prices led to rapidly rising revenues over that period. Thus, there has been no further consolidation in the nine additional years of data available since the two Solís *et al.* studies, raising the question of IFQs' efficacy in reducing overcapacity.

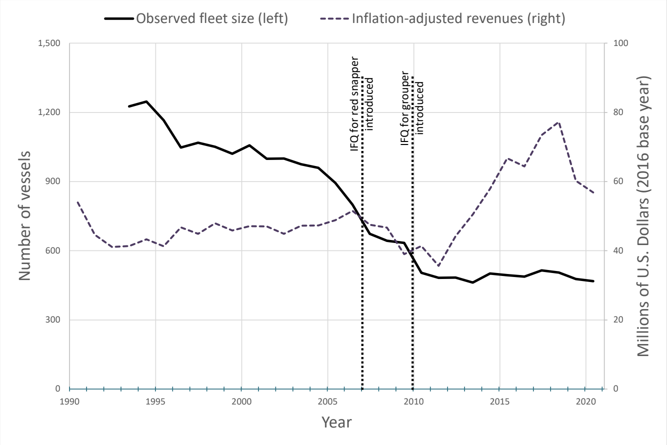

Figure 1: Count of active vessels and fleet-wide revenues

We deem a vessel as active if it hauled in more than 10 pounds of red snapper in a given year, though setting the thresholds at 100 or 200 pounds of annual catch yields qualitatively similar graphs. Interestingly, Figure 1 reveals that a significant fleet contraction from 960 to 800 vessels already took place between 2004 and 2006, that is, in the two years *prior* to the implementation of an IFQ for the dominant species in 2007, leaving us to speculate whether contests for catch shares may have inflated vessel participation prior to the expected IFQs, a behavior that has been documented for the Mid-Atlantic surf clam fishery (Brandt 2007). The 2007 introduction of the red snapper IFQ coincided with a contraction from 800 to about 670 vessels, while the 2010 introduction of the grouper and tilefish IFQs coincided with a drop from 630 to about 500 vessels.

IFQ-driven fleet size reductions have also been documented in other fisheries, such as the Mid-Atlantic clam and quahog fishery (Adelaja *et al.* 1998) and the Pacific Coast groundfish fishery (Lian *et al.* 2010). Nevertheless, the shedding of excess capacity can be slow as capital investments are somewhat irreversible (Clark *et al.* 1979) and because operators of less efficient vessels may take a wait-and-see approach (Weninger & Just 1997). By contrast, the 2005 IFQ introduction in the Bering Sea crab fishery led to a remarkably *immediate* 65% reduction in the total number of vessels relative to the previous years (see Figure 1 in Reimer *et al.* 2014). Thus, even if stickiness of over-capacity after the introduction of an IFQ program may be common, it is not a necessity, raising the question of what factors are key for a fishery's rapid adjustment to the new policy environment. Conceivably, the single-species nature of the crab fishery may have been a contributing factor, whereas IFQ programs may be less effective in reducing capacity in complicated multi-species fisheries (Squires & Kirkley 1996).

We first proceed by developing a simple bioeconomic model of production with identical vessels, which, combined with a market-clearing condition, leads to a first set of comparative statics results for fleet size. These theoretical results indicate that biomass recovery will lead to fleet expansion under CFQs, but to fleet contraction under IFQs. Furthermore, dockside prices are a determinant of fleet size under CFQs, but not under IFQs. In section 3, we extend the model to account for heterogeneity in vessel productivity, preparing the groundwork for numerical simulations to derive year-by-year theoretical fleet sizes. These simulations serve to gauge the relative importance of the various factors at play. The data are presented in section 4, and the results are reported in section 5, along with robustness checks. We also address the role of expectations in that section. The results suggest that only about half of the 2004-2010 contraction was due to the switch from a common-pool to a tradable quota system, the remainder being driven by the simultaneously occurring biomass recovery on the one hand and a participation-inflating contest for catch shares prior to the regime change on the other.

2 A simple model

To understand industry-wide adjustments, we combine vessel-level decision-making and market clearing. Here we derive comparative statics results by focusing on the intuitive symmetrical case of identical vessels. We tackle the more realistic case of participation with a set of heterogeneous vessels, which underpins our simulations, in the following section.

A vessel's annual harvest is specified by the standard bi-linear bioeconomic production function

$$h_t = X_t d_t, \tag{1}$$

where X_t stands for stock abundance and d_t for the number of days of operation. (Here and throughout, we shall use capital letters to denote exogenously determined variables.) Denote $c(d_t)$ the cost of operating d_t days in a year, where c is increasing and convex. While each day of operation is thus assumed to be equally productive, cost per day of operation is increasing, an assumption justified by the growing difficulty of avoiding poor weather conditions and scheduling vessel maintenance, as well as the increasing opportunity cost of time and the need for rest.

For the case of an IFQ regime, let τ_t denote the per-pound quota allocation transfer (or rental) price; for the case of a CFQ regime enforced by seasonal closures of the fishing grounds, let $o_t \leq 365$ denote a year's number of open days. Letting P_t stand for the per-pound dockside price for fish, the vessel's profit-maximization problem is then:

$$\max_{d_t} \Pi_t = (P_t - \tau_t) X_t d_t - c(d_t), \tag{2}$$

subject to $d_t \leq o_t$. In what follows, we drop subscripts for notational ease when no confusion is possible.

The case of the common-pool quota

Under a CFQ regime, $\tau = 0$. Letting n stand for the number of participating vessels, the regulator will set the number of open days o so that fleet-wide output $n \cdot h$ equals TAC Q, i.e.,

$$o = \frac{Q}{nX}. \tag{3}$$

A vessel's annual profit is then given by

$$\Pi = P\frac{Q}{n} - c\left(\frac{Q}{nX}\right) - F, \tag{4}$$

where F stands for a firm's annualized fixed costs, such as the rental cost of capital and permits. Taking a long-run perspective, new vessels will enter when profit is positive and exit when profit is negative. The equilibrium number of vessels n is obtained when profits are zero. $\Pi = 0$ therefore implicitly defines fleet size n, allowing us to derive comparative statics results. Using the implicit function theorem (and relegating the routine, but tedious, proofs to the appendix), we obtain

$$\frac{dn}{dX} = -\frac{\partial \Pi}{\partial X}\bigg/\frac{\partial \Pi}{\partial n} = \frac{c'(o)}{PX - c'(o)} > 0 \tag{5}$$

$$\frac{dn}{dQ} = -\frac{\partial \Pi}{\partial Q}\bigg/\frac{\partial \Pi}{\partial n} = \frac{n}{Q} > 0 \tag{6}$$

$$\frac{dn}{dP} = -\frac{\partial \Pi}{\partial P}\bigg/\frac{\partial \Pi}{\partial n} = \frac{nX}{PX - c'(o)} > 0 \tag{7}$$

Rather intuitively, fleet size n is increasing in ex-vessel price P, TAC Q, and stock abundance X. Furthermore, if regulators were to allow TAC to increase in lock-step with biomass, i.e., $dQ/Q = dX/X$, the fleet would also grow at about the same rate as biomass, since for n large,

$$\frac{dn}{n} = \frac{n}{Q}\frac{dQ}{n} + \frac{c'(o)}{PX - c'(o)}\frac{dX}{n} = \left(\frac{PX - c'(o) + c'(o)/n}{PX - c'(o)}\right)\frac{dX}{X} \approx \frac{dX}{X}. \tag{8}$$

The case of individual tradable quotas

Under an IFQ regime, the fishery does not rely on seasonal closures, and we assume that the open season constraint is no longer binding. At the market-clearing allocation price τ, fleet-wide aggregate demand for quota equals TAC Q. Thus, the first-order condition at the interior solution implies

$$\tau = P - \frac{1}{X}c'\left(\frac{Q}{nX}\right). \tag{9}$$

Inserting the solution for τ into annual profit, we obtain

$$\Pi = \frac{Q}{nX}c'\left(\frac{Q}{nX}\right) - c\left(\frac{Q}{nX}\right) - F. \tag{10}$$

As before, the zero-profit condition implicitly defines the equilibrium fleet size n, yielding the comparative statics results:

$$\frac{dn}{dX} = -\frac{\partial \Pi}{\partial X}\bigg/\frac{\partial \Pi}{\partial n} = -\frac{n}{X} < 0 \tag{11}$$

$$\frac{dn}{dQ} = -\frac{\partial \Pi}{\partial Q}\bigg/\frac{\partial \Pi}{\partial n} = \frac{n}{Q} > 0 \tag{12}$$

$$\frac{dn}{dP} = -\frac{\partial \Pi}{\partial P}\bigg/\frac{\partial \Pi}{\partial n} = 0 \tag{13}$$

We again find that fleet size is increasing in TAC Q. However, in contrast to the CFQ case, fleet size is decreasing in stock abundance X. Furthermore, it is independent of dockside price P. Finally, note that if regulators systematically set the TAC proportionally to biomass, the fleet size would not change, since $dQ/Q = dX/X$ implies

$$dn = \frac{dn}{dQ}dQ + \frac{dn}{dX}dX = \frac{n}{Q}dQ - \frac{n}{X}dX = 0. \tag{14}$$

To summarize, in contrast to the CFQ case, under the IFQ regime, dockside prices do not affect fleet size. The reason is that the "margin" $P - \tau$ is, in fact, invariant in P. Second, an increase in biomass implies an increase in fleet size under the CFQ regime, but a decrease under the IFQ regime: as active vessels increase their outputs, fewer vessels are needed to meet the TAC.

3 Heterogeneous vessels and model operationalization

We verify the model's predictive ability through numerical simulations. To operationalize our model, we now assume that vessels have heterogeneous capacities K_i, which we define as a vessel's second-largest historical daily catch of all reef fish species, the second-largest value serving to avoid any outliers caused by erroneous data entry. The capacity distribution for the 3,598 commercial U.S. Gulf of Mexico vessels that caught at least 10 pounds of red snapper in any year between 1993 and 2006 is shown along a logarithmic scale in Figure 2.

In a given year, we use the total allowable catch, biomass estimates, the observed catch price, and estimated cost parameters to predict which among the 3,598 vessels would be active in the long run, *if* fishers had Markovian expectations and believed that current conditions would persist. Of course, since short-run shutdown decisions ignore sunk costs, our predicted fleet size must be interpreted as a mere attractor. Furthermore, because of hysteresis, convergence to the attractor can be slow. Fishers, by-and-large, tend to be attached to their profession and consider it a way of life. The decision to leave the industry thus goes beyond mere financial calculus; it is an emotional process that requires time. Furthermore, a positive cash flow may mask an economic loss when the implicit opportunity costs for labor and allocations are not properly accounted for. Reluctance to exit may also

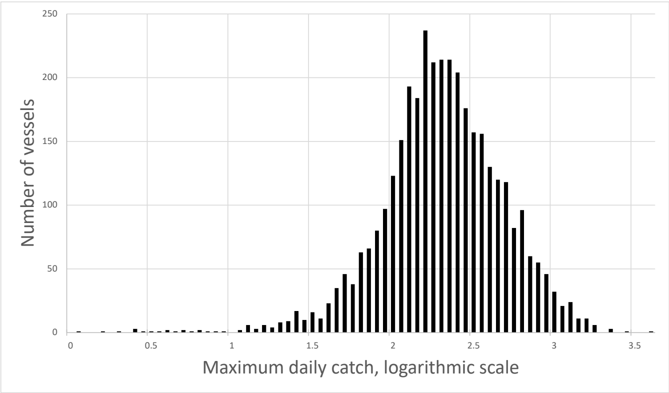

Figure 2: Vessels, ranked by maximum daily output

have rational grounds as fishers prosecute currently unregulated and lower-valued fish in hopes of staking claims to potential future IFQ programs, a motive we further explore in the results section.

In year t, vessel i's production function is given by the extended bioeconomic production function

$$h_{it} = K_i X_t d_{it}. \tag{15}$$

Workers are compensated according to the customary lay system and paid a share $\ell = 29\%$ of revenue. Among variable costs, we distinguish between those costs that are roughly proportional to catch, a constant per unit cost v_t associated with consumables such as bait and ice, and those costs that are best thought of as being proportional to days at sea d_t, such as fuel and groceries, w_t standing for the average vessel's per-day cost of operation. The values for v_t and w_t are annual averages inferred from the Logbook Program, where captains report expenditures for every trip. Net price P_t, net of labor and consumables, is then

$$P_t = (1 - \ell)p_t - v_t, \tag{16}$$

where p_t stands for the observed ex-vessel (or dockside) price of the average catch, also inferred from the Logbook Program and calculated as revenue from all reef fish species divided by the corresponding quantity in pounds. Furthermore, we assume that the cost per day at sea is an accelerating function, capturing the idea of increasing opportunity costs and the reduced availability of fair-weather days. In addition, since a more productive vessel typically has a larger crew and requires more fuel to operate, we assume that daily cost also depends on K_i. We specify

$$c_{it} = w_t K_i^{\varepsilon} d_{it}^{1+\gamma}, \tag{17}$$

where $\gamma > 0$ and $0 < \varepsilon \leq 1$. Finally, we make the assumption that a vessel's annualized fixed cost F associated with depreciation, docking fees, repairs and maintenance, permits, and taxes is increasing and concave in capacity K_i. The concavity assumption reflects the stylized idea that doubling the vessel's capacity does not double its purchasing price or other costs associated with its upkeep. We specify a vessel's fixed cost as:

$$F(K_i) = \sigma K_i^{\delta}, \tag{18}$$

where σ and δ are positive.

The optimization problem is then:

$$\max_{d_{it}} \Pi_{it} = (P_t - \tau_t) K_i X_t d_{it} - w_t K_i^{\varepsilon} d_{it}^{1+\gamma}, \text{ s.t. } d_{it} \leq o_t, \tag{19}$$

with corner solution $d_{it}^* = o_t$ and interior solution

$$d_{it}^* = \left(\frac{(P_t - \tau_t) X_t K_i^{1-\varepsilon}}{(1+\gamma) w_t} \right)^{\frac{1}{\gamma}}. \tag{20}$$

Our computational algorithm is simple: For the case of the common-pool quota regime, we set allocation price $\tau_t = 0$ and then progressively increase o_t, the length of the fishing season, from 0 days on up. For the case of individual tradable quotas, we set $o_t = 365$ and then progressively decrease τ_t from P_t (where there is no margin and thus no output) on down. At each step, we aggregate the vessels' outputs, conditional on earning a positive profit. The algorithm stops and produces the count of participating vessels when the aggregate output corresponds to the total allowable catch (TAC).

It is natural to ask whether the predictions derived from the simple symmetrical model of the previous section carry over to the case with heterogeneous vessel capacity. Let us rank vessels in decreasing order of capacity. Denote $\mathcal{P} \subseteq \{1, 2, \ldots, n\}$ the subset of active vessels, implicitly assuming that if production is profitable for vessel j, it must also be profitable for vessel $j - 1$. This is not an innocuous assumption, as it may be violated when the cost of capital grows too fast relative to the vessel's capacity. As before, we drop the time subscripts for notational ease, since no confusion is possible.

Under the common-pool quota regime, fisheries management will adjust the number of open days o so that the fleet-wide aggregate demand for quota equals TAC Q:

$$\sum_{i\in\mathcal{P}} h_i = oX \sum_{i\in\mathcal{P}} K_i \quad = \quad Q, \tag{21}$$

so that

$$o = \frac{Q}{X\sum_{i\in\mathcal{P}} K_i}. \tag{22}$$

Under the (long-run) zero-profit condition for the active fleet's marginal vessel ι, we have

$$PXK_\iota d - wK_\iota^\varepsilon d^{1+\gamma} - \sigma K_\iota^\delta = 0. \tag{23}$$

If the open-season constraint is binding for the marginal vessel, we can substitute Equation (22) into Equation (23) to obtain

$$P\frac{Q}{S_\iota}K_\iota - \sigma K_\iota^\delta - w\left(\frac{Q}{XS_\iota}\right)^{1+\gamma}, \tag{24}$$

where $S_\iota = \sum_{j>\iota} K_j$. While there is no closed-form solution for K_ι, we can apply the implicit function theorem to obtain the comparative statics results

$$\frac{dK\iota}{dX} = -\frac{\partial\Pi}{\partial X}\Big/\frac{\partial\Pi}{\partial K\iota} < 0 \tag{25}$$

$$\frac{dK\iota}{dQ} = -\frac{\partial\Pi}{\partial Q}\Big/\frac{\partial\Pi}{\partial K\iota} < 0 \tag{26}$$

$$\frac{dK\iota}{dP} = -\frac{\partial\Pi}{\partial P}\Big/\frac{\partial\Pi}{\partial K\iota} < 0 \tag{27}$$

provided the "scale economy" condition $\delta < 1$ holds, i.e., the cost of capital must not increase faster than its capacity. In that case, the threshold vessel capacity K_ι decreases (and thus vessel participation increases) if biomass X, TAC Q, or dockside price P increase, results in line with those for the symmetrical case.

Turning to the IFQ system and assuming interior solutions for all participating vessels, at the market-clearing allocation transfer price τ, fleet-wide aggregate demand for quota equals TAC Q:

$$\sum_{i\in\mathcal{P}} h_i = \sum_{i\in\mathcal{P}} XK_i\left(\frac{(P-\tau)XK_i}{(1+\gamma)w}\right)^{\frac{1}{\gamma}} \quad = \quad Q, \tag{28}$$

so that

$$P - \tau = \left(\frac{Q}{X S_{\mathcal{P}}} \right)^{\gamma} \frac{(1+\gamma)w}{X}, \tag{29}$$

where $S_{\mathcal{P}} = \sum_{j \in \mathcal{P}} K_j^{\frac{1+\gamma}{\gamma}}$. For vessel i, the optimal annual number of days at sea is then

$$d_i = \frac{Q}{X S_{\mathcal{P}}} K_i^{\frac{1}{\gamma}}, \tag{30}$$

its annual output

$$h_i = \frac{Q}{S_{\mathcal{P}}} K_i^{\frac{1+\gamma}{\gamma}}, \tag{31}$$

and its profit

$$\Pi_i = \gamma w \left(\frac{Q}{X S_{\mathcal{P}}} \right)^{1+\gamma} K_i^{\frac{1+\gamma}{\gamma}} - \sigma K_i^{\delta}. \tag{32}$$

As before, the zero-profit condition implicitly defines threshold capacity K_ι and, for $\delta < 0$, yields the comparative statics results:

$$\frac{dK\iota}{dX} = -\frac{\partial \Pi}{\partial X} \bigg/ \frac{\partial \Pi}{\partial K\iota} > 0 \tag{33}$$

$$\frac{dK\iota}{dQ} = -\frac{\partial \Pi}{\partial Q} \bigg/ \frac{\partial \Pi}{\partial K\iota} < 0 \tag{34}$$

$$\frac{dK\iota}{dP} = -\frac{\partial \Pi}{\partial P} \bigg/ \frac{\partial \Pi}{\partial K\iota} = 0 \tag{35}$$

Threshold vessel capacity K_ι increases (and thus vessel participation decreases) if biomass X increases or if TAC Q decreases, while changing dockside prices P have no impact on the participation of the marginal vessel. These results again correspond to those of the symmetrical case. In particular, they hold for the contractionary effect of biomass on fleet size: growing biomass increases output per unit of effort, and even more so for large vessels. However, under IFQs, the improved margin earned by inframarginal vessels is captured by higher allocation prices. For the marginal vessels, the increase in allocation prices is larger than the increases in productivity, prompting their exit as they lease their catch shares to more efficient producers.

4 Data and benchmark calibration

We use various data sources to calibrate our fleet size model for the 1990-2020 period of observation. Daily trip-level data stem from the National Marine Fisheries Service (NMFS) Southeast Coastal Fisheries Logbook Program, which contains trip-level landings and cost information for every vessel. Our data source for a wide range of vessel characteristics and vessel registration is the Permit Information Management System (PIMS) for red snapper and grouper. These data are summarized in Table 1.

TAC, dockside prices, and costs

Annual commercial landing statistics were obtained from NOAA's Office of Science and Technology. Since we do not deal explicitly with the dynamics of multi-species fisheries, we merely aggregate the TACs for an overall measure of allowed prosecution. We also produce a price index of dockside prices, a weighted average for the various species, simply defined as aggregate revenue from all relevant species divided by their volume in pounds. The price index and the aggregate TAC are shown in Figure 3.

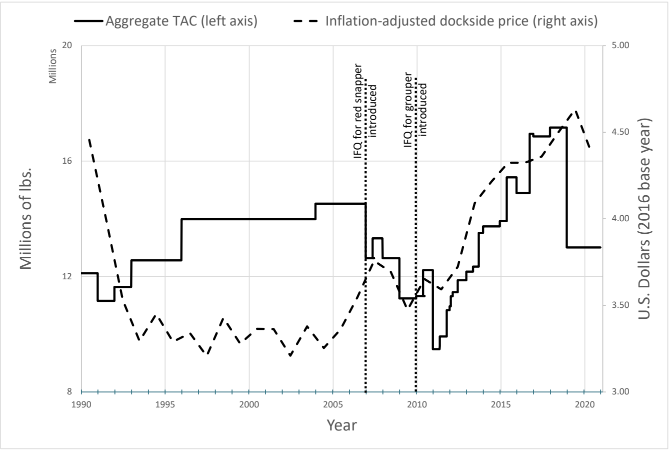

Figure 3: TAC and dockside prices

The Logbook program occasionally collects and reports various costs for variable inputs such as fuel, bait, tackles, ice, groceries, and miscellaneous supplies. We distinguish between costs best thought of as proportional to catch, such as ice and bait, and costs best thought of as proportional to trip duration, such as fuel and groceries. The data are incomplete prior to 2003

Year	**Combined TAC (lbs)**	**Biomass (metric tons)**	**Share fish 3+ yrs. old**	**Dockside price per lb.**	**Cost ice, bait per lb. of catch**	**Cost fuel, etc. per day at sea**
1990		98,624	0.592	4.46	0.30	318.38
1991		99,077	0.534	4.00	0.30	311.36
1992		99,541	0.643	3.53	0.29	306.48
1993	12,556,757	105,076	0.661	3.29	0.29	300.15
1994	12,556,757	102,952	0.704	3.45	0.28	297.37
1995	12,556,757	100,935	0.668	3.29	0.27	317.81
1996	13,989,189	108,011	0.674	3.34	0.26	323.91
1997	13,989,189	108,293	0.668	3.21	0.26	318.47
1998	13,989,189	104,382	0.738	3.43	0.26	310.72
1999	13,989,189	111,984	0.737	3.28	0.26	291.98
2000	13,989,189	116,298	0.746	3.36	0.26	342.84
2001	13,989,189	117,500	0.717	3.36	0.25	312.74
2002	13,989,189	124,267	0.733	3.21	0.25	305.85
2003	13,989,189	124,573	0.752	3.38	0.32	378.05
2004	14,529,189	127,359	0.717	3.25	0.23	346.59
2005	14,529,189	124,169	0.688	3.36	0.22	315.91
2006	14,529,189	106,685	0.674	3.55	0.24	337.49
2007	13,326,486	113,542	0.700	3.76	0.22	366.50
2008	12,637,297	118,188	0.745	3.69	0.20	356.62
2009	11,237,297	124,231	0.800	3.47	0.19	291.90
2010	12,220,991	134,252	0.843	3.65	0.17	265.01
2011	10,830,901	138,564	0.849	3.59	0.21	338.85
2012	11,867,613	144,511	0.863	3.72	0.18	342.59
2013	13,510,054	150,732	0.873	4.09	0.20	358.37
2014	13,734,054	154,757	0.876	4.22	0.20	321.76
2015	15,446,270	161,173	0.885	4.32	0.20	272.58
2016	16,947,297	164,814	0.889	4.32	0.20	263.03
2017	16,853,604	164,792	0.900	4.36	0.22	245.12
2018	17,162,613	170,534	0.900	4.50	0.22	251.10
2019	13,007,838	175,550	0.900	4.63	0.22	255.65
2020	13,007,838	180,566	0.900	4.37	0.22	258.84

All prices in U.S. Dollars, adjusted for inflation, 2016 base year. Some biometric data are based on extrapolations.

Table 1: Data used to calibrate model

and do not exist for years prior to 1993. For the 1988 to 1992 period, we estimate cost items on the basis of fuel prices and producer price indexes. The estimates are shown in Figure 4.

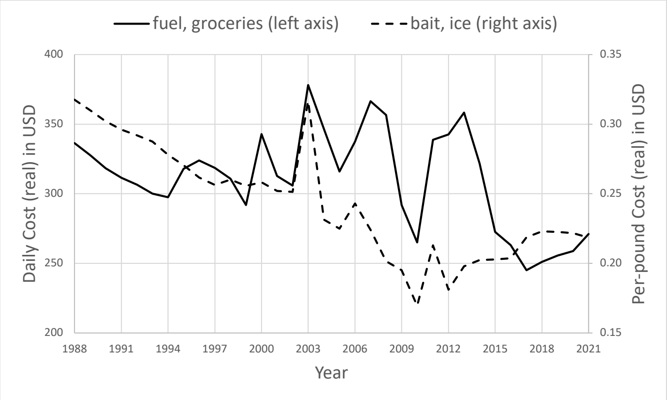

Figure 4: cost estimates

Based on the annual price and cost data for the various species, and the assumption that the crew are paid 29% of revenue (net of allocation cost under IFQs), we can produce a typical cost decomposition, shown in Figure 5, for a pound of catch of the representative species.

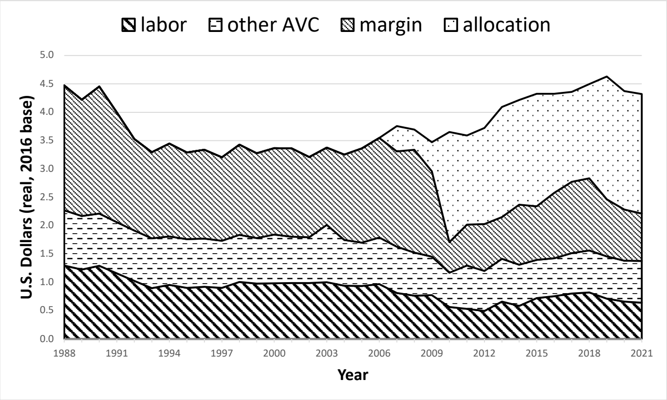

Figure 5: Cost accounting

Accessible biomass

Biomass estimates for various (but not all) concerned species are provided in various SEDAR (SouthEast Data, Assessment, and Review stock assessment data) reports. Figure 6 shows the aggregate biomass for the three dominant species: red grouper, gag grouper, and red snapper. However, not all biomass is accessible by fishers. Notably, minimum size limits first introduced in 1990 imply that only fish of a certain length (typically, 12 inches long) can be kept, while smaller (and thus younger) fish must be discarded. Figure 7 shows the share of red snapper that are at least three years old, the only species for which we have such data. We use this as a multiplicative factor when computing accessible biomass.

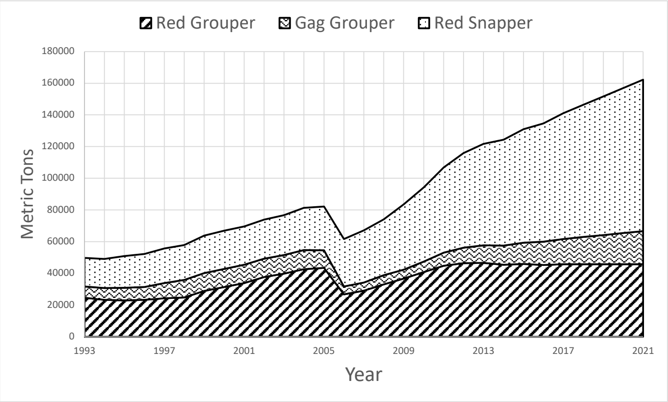

Figure 6: Biomass estimates for three dominant reef fish species in the Gulf of Mexico

The benchmark calibration

Let α be a scale parameter for the production function, so that $h_{it} = \alpha K_i X_t d_{it}$, and let β be a scale parameter for the variable cost function, so that $c_{it} = \beta w_t K_i^{\varepsilon} d_{it}^{1+\gamma}$. Let $F_\iota = F_0 + \sigma K_\iota^\delta$ stand for the the threshold vessel's fixed cost, where F_0 is fixed cost that is independent of vessel capacity, such as for permits or docking, which we estimate at \$1,500. For vessel i, we then have

$$F_i = F_0 + (F_\iota - F_0)\left(K_i / K_\iota\right)^\delta . \tag{36}$$

We select 1993 as the benchmark year, during which 1,226 vessels were active, and therefore calibrate the production function around threshold

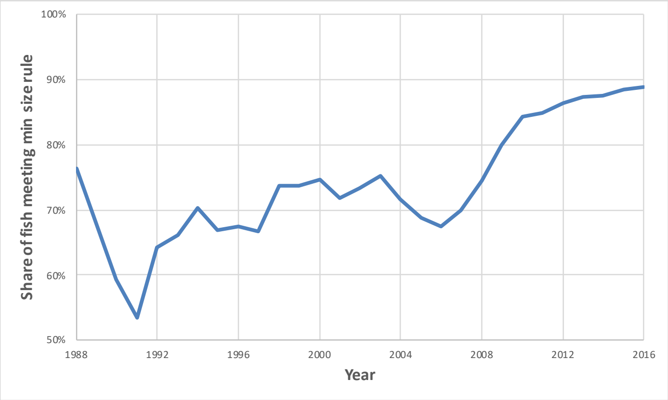

Figure 7: Estimated share of red snapper meeting size requirement

vessel $\iota = 1,226$, for which profit would have been zero. The default values of cost parameters are initially set at plausible values $\gamma = 0.9$, $\varepsilon = 0.8$, and $\delta = 0.5$, leaving the exploration of alternative values to our sensitivity analysis. Thus

$$\alpha = \frac{h_{1226,1993}}{K_{1226}X_{1993}d_{1226,1993}} = \frac{8,285}{265.77 \times 0.64 \times 31} = 1.56; \tag{37}$$

$$\beta = \frac{c_{it}}{K_i^{\varepsilon} d_{it}^{1+\gamma}} = \frac{6,138}{265.77^{0.6} 31^{1.8}} = 0.00103; \tag{38}$$

$$\begin{aligned} F_\iota &= P_{1993}h_{1226,1993} - c_{1226,1993} \\ &= ((1-0.29) \times 3.29 - 0.287) \times 8,285 - 6,138 = 7,638 \end{aligned} \tag{39}$$

are the only calibrated parameters.

5 Results

5.1 Baseline results

While we have no historical fleet size data for 1990-1992 for comparison, our simulations, shown in Figure 8, produce a significant drop in the number of vessels during that initial CFQ period, mainly driven by the drop in dockside prices. The model then predicts a slight upward trend in the number of vessels through the remainder of the CFQ period. Turning to the post-2007 IFQ regime, the model predicts a sharp 60% drop in the number of operating vessels during the 2007-2010 transition period, followed by a soft increase until 2018 and another sharp drop in 2019. To understand these

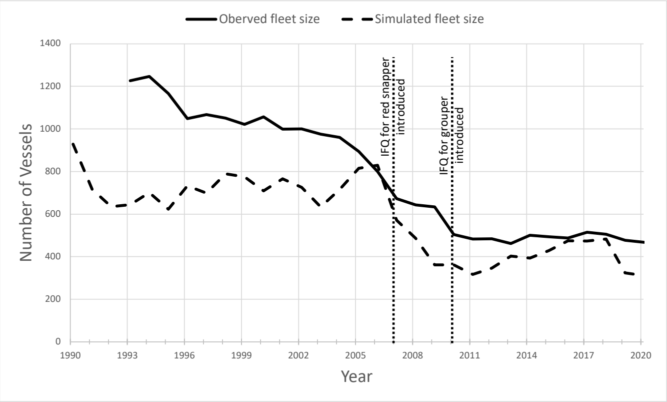

Figure 8: Model-generated fleet size

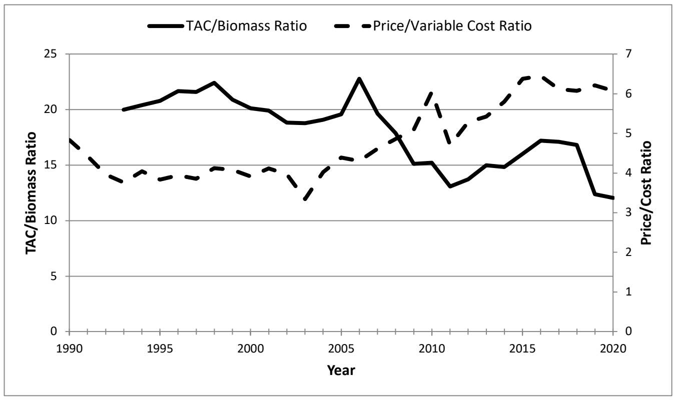

Figure 9: Two key ratios

changes, we focus on two ratios, presented in Figure 9: dockside prices relative to variable costs (which depend to a large extent on fuel prices) and the TAC relative to accessible biomass. The ups and downs in the number of participating vessels appear to be driven chiefly by changes in the price ratio during the CFQ period and by changes in the abundance ratio during the IFQ period.

Remarkably, much of the decrease in fleet size during the initial IFQ period coincides with a sharp drop in the abundance ratio, thus providing an alternative, or at least complementary, explanation to the shift in management regime. Thus the concurrence of two factors, namely TAC decreases along with sustained biomass recovery, contributed to the significant 2007-2010 fleet size reduction heretofore solely associated with the mere introduction of IFQs.

To separately identify the two factors, we ran a counterfactual scenario to see how the fleet size would have evolved if the IFQ regime had been in place all along. The result is shown in Figure 10. The simulated fleet size under the counterfactual assumption of an IFQ regime in 2006 is slightly lower than the simulated fleet size for 2007. Thus the regime shift is solely responsible for the 2006-2007 fleet contraction. However, the subsequent 2007-2010 decrease was solely driven by the decreasing TAC-to-biomass ratio, even if this decrease would not have occurred under the old common-pool system. Indeed, under the latter, our earlier comparative statics results suggest that the larger biomass would have led to a fleet expansion.

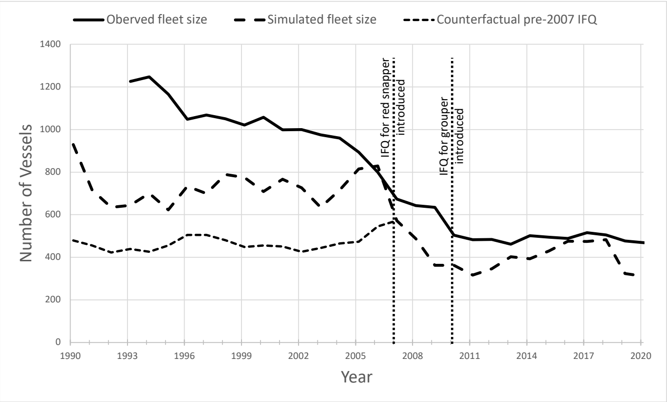

Figure 10: Counterfactual pre-2007 IFQ

5.2 Sensitivity analysis

In the absence of estimates for cost parameters γ, ε, and δ, we ran our simulation with alternative parameter values. The results are shown in Figure 11. While the various parameter values affect the amplitude of fleet size variation, the main results are robust: worsening conditions in the early nineties led to pressure to exit, but the long-run equilibrium fleet size remained relatively steady for the remainder of the CFQ period. The switch to IFQs would then bring about the expected contraction in fleet size, though with an assist from an increase in accessible biomass combined with a decrease in TAC.

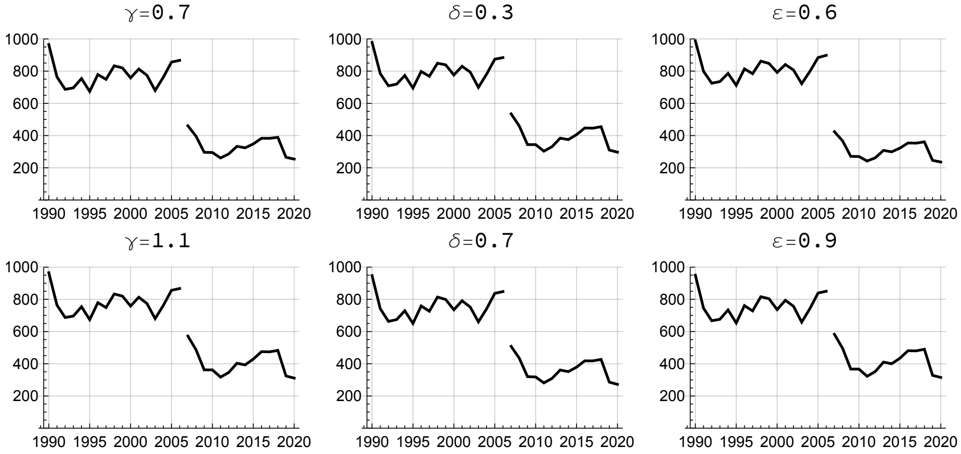

Figure 11: Sensitivity analysis

5.3 The role of expectations

Our static approach stresses intuition and conveniently eschews the complications of a firm's dynamic optimal investment problem and the modeling of expectations, rational or otherwise, about future profitability. These expectations would hinge on the possibility of future regulatory shifts, changes in biomass, the evolution of market demand for fish and catch prices, and the number of competitors. A more intricate model could also more explicitly consider the role of sunk costs, allowing entry and exit to occur simultaneously, albeit at the cost of tractability.

However, our narrow consideration of contemporaneous profit would be egregiously counterfactual if it did not account for the strong incentive to build up a catch share history in anticipation of a future IFQ regime. Indeed, while the 2007 IFQ for red snapper was officially announced in 2005 with initial catch share allocations to be based on catch history over the seven- to fifteen-year period up to 2004 (depending on the type of license held), awareness about the policy change long preceded the official announcement. Indeed, workshops and public hearings about a potential implementation of an IFQ program for red snapper had already occurred between 1992 and 1995, much of the debate focusing on the contentious issue of initial allocations (Keithly 2002). The Gulf Council eventually settled on an individual allocation of shares based on an operator's best two years between 1990 and 1992, and the resolution was passed for an IFQ system starting in April of 1996. However, this was not to be, as the U.S. Congress had placed a moratorium on all new IFQ programs in the meantime. The moratorium was lifted in October of 2000, and the Gulf Council soon restarted the development of the current red snapper IFQ program. Arguably, then, the change in policy came as no surprise to fishers, and, while difficult to quantify, it must have been clear to fishers that a pound of catch was worth more, perhaps considerably more, than just the dockside price. And indeed, despite the derby fishing-induced market glut and the depressed prices during the CFQ period, the pronounced decline in fleet size only began in 2005, the first year to be excluded from historical catch considerations.

To simulate the effect of expectations about future IFQs, we add one dollar to the historical real dockside prices. We justify this admittedly blunt adjustment as follows: with a 10% intertemporal discount rate, the present value of one-pound equivalent catch share, leased for \$1.50 every year in perpetuity, is \$15. The \$1 figure is obtained by dividing this present value by the number of pounds needed to eventually earn a permanent one-pound catch share equivalent, assuming that fishers needed to catch a pound of an IFQ-targeted species each year over the 15-year period from 1990 to 2004. As seen in Figure 12, if fishers believed that the claim to future catch shares increased the value of a pound of fish by a dollar, the fleet size prior to the 2005 official announcement would have been 40 to 50% larger, bringing it closer to the observed size.

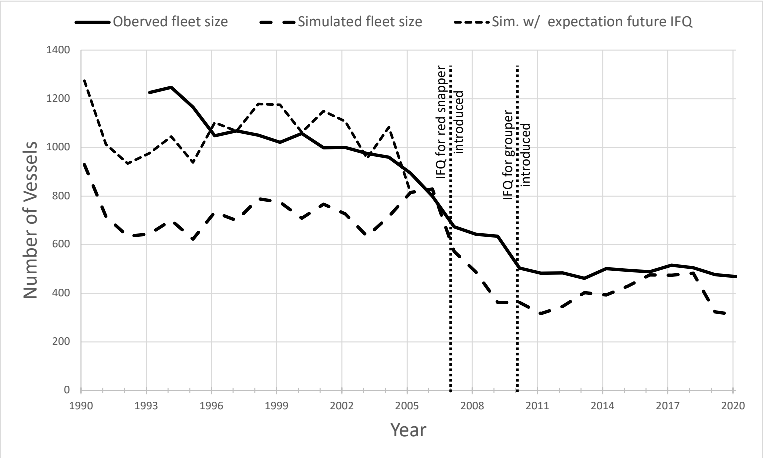

Figure 12: Pre-2007 fleet size when future IFQ is expected

6 Conclusion

With the switch from common-pool to tradable quota programs, it was widely expected that low-capacity vessels would sell their allocations to more efficient ones; indeed, both the data and our model are consistent with a fleet size contraction from 2007 to 2010. However, our results also suggest that the regime switch does not provide the sole explanation. Rather, three other factors offer complementary explanations. First of all, the switch to IFQs coincided with decreases in the TAC. Second, sustained biomass recovery boosted vessel participation under the common-pool regime but had the opposite effect on fleet size under the IFQ system. Third, a contest for catch shares prior to the expected introduction of IFQs may account for high vessel participation during much of the common-pool era and may explain the 25% drop ahead of the regime change.

While the expectation of a future IFQ may have temporarily inflated the fleet size, the actual implementation was clearly successful in reducing excess capacity. Furthermore, we argue that the additional subsequent contraction due to biomass recovery was only possible because of the catch share system, since the same biomass recovery under a common pool system would have led an expansion of the fleet.

While not the object of this paper, IFQs were also successful in eliminating derby fishing behavior, thereby improving safety and reducing dockside price volatility. Learning about the efficacy and potential shortcomings of the current IFQ programs can provide guidance in the development of future IFQ programs for other fisheries, both commercial and recreational. For example, the highly migratory species (HMS) group is considering a bycatch catch share program for bluefin tuna, while the Southeastern Fisheries Council is contemplating a new IFQ program for the for-hire red snapper fishery in the Gulf of Mexico and a recreational tag program for low allowable catch limit (ACL) species in the South Atlantic.

In particular, future IFQ implementations should avoid a pitfall described in this paper, namely rent-seeking behavior that may have both delayed the transition and accentuated inefficiencies prior to implementation. Indeed, such behavior may still be associated with the prosecution of so far unregulated and lower-valued fish in hopes of staking claims to potential future IFQ programs, a complementary activity that may continue to justify the decision not to exit the market for red snapper, grouper, and tilefish.

The contentious political process leading up to the IFQ implementation also led to an uneven distribution of fishing privileges, which combined with the observed fleet contraction may have had consequences on the fishing community that deserve further investigation. Arguably, a fisher's income may be less volatile if he owns both a vessel and catch shares: ownership of catch shares reduces financial risk to the extent that dividends (τ) are negatively correlated to the operational margin ($P-\tau$). This consideration would imply that shares are more valuable to operators than to non-operators, who would be outbid.

Finally, we treat the various reef fish species as an aggregate and therefore ignore the biological and economic dynamics of multi-species fisheries. Future research could reexamine the optimal design of IFQ rules and management policies in the context of complex fisheries and explore ways to unlock efficiency gains, such as from diversification in production (Solís *et al.* 2020), for instance by reducing the wasteful discards of bycatch. Such additional gains in efficiency could, in turn, lead to further adjustments of fleet sizes to optimal levels.

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A Proofs for comparative statics results

A.1 Homogeneous vessels

A.1.1 CFQ case

The implicit function is

$$\Pi = P\frac{Q}{n} - c\left(\frac{Q}{nX}\right) - F = 0. \tag{40}$$

Since the complementary slackness condition at the corner solution implies $PX - c'() > 0$, we can sign the following partial derivatives:

$$\frac{\partial \Pi}{\partial X} = \frac{Q}{nX^2} \cdot c'() > 0 \tag{41}$$

$$\frac{\partial \Pi}{\partial Q} = \frac{X}{n}\left(PX - c'()\right) > 0 \tag{42}$$

$$\frac{\partial \Pi}{\partial P} = \frac{Q}{n} > 0 \tag{43}$$

$$\frac{\partial \Pi}{\partial n} = -\frac{Q}{n^2 X}\left(PX - c'()\right) < 0 \tag{44}$$

The comparative statics results follow.

A.1.2 IFQ case

The implicit function is

$$\Pi = \frac{Q}{nX} c'\left(\frac{Q}{nX}\right) - c\left(\frac{Q}{nX}\right) - F = 0 \tag{45}$$

Since cost c is convex in d, we can sign the partial derivatives:

$$\frac{\partial \Pi}{\partial X} = -\frac{Q^2}{n^2 X^3} \cdot c''() < 0 \tag{46}$$

$$\frac{\partial \Pi}{\partial Q} = \frac{Q}{n^2 X^2} \cdot c''() > 0 \tag{47}$$

$$\frac{\partial \Pi}{\partial P} = 0 \tag{48}$$

$$\frac{\partial \Pi}{\partial n} = -\frac{Q^2}{n^3 X^2} \cdot c''() < 0 \tag{49}$$

The comparative statics results follow.

A.2 Heterogeneous vessels

A.2.1 CFQ case

The implicit function is

$$\Pi = P\frac{Q}{S_\iota} K_\iota - w\left(\frac{Q}{XS_\iota}\right)^{1+\gamma} - \sigma K_\iota^\delta = 0, \tag{50}$$

Since the complementary slackness condition at the corner solution implies that marginal revenue exceeds marginal cost, we can sign the partial derivatives:

$$\frac{\partial \Pi}{\partial X} = \frac{(1+\gamma)w}{X}\left(\frac{Q}{XS_\iota}\right)^{1+\gamma} > 0 \tag{51}$$

$$\frac{\partial \Pi}{\partial Q} = P\frac{K_\iota}{S_\iota} - \frac{(1+\gamma)w}{XS}\left(\frac{Q}{XS_\iota}\right)^{\gamma} > 0 \tag{52}$$

$$\frac{\partial \Pi}{\partial P} = \frac{K}{S} > 0 \tag{53}$$

$$\frac{\partial \Pi}{\partial K_\iota} \approx \frac{1}{K_\iota}\left(P\frac{Q}{S_\iota}K_\iota - \sigma K_\iota^\delta\right) > 0 \tag{54}$$

The comparative statics results follow.

A.2.2 IFQ case

The implicit function is

$$\Pi = \gamma w\left(\frac{Q}{XS_{\mathcal{P}}}\right)^{1+\gamma} K_\iota^{\frac{1+\gamma}{\gamma}} - \sigma K_\iota^\delta = 0, \tag{55}$$

so that

$$\frac{\partial \Pi}{\partial X} = -\frac{\gamma(1+\gamma)w}{X}\left(\frac{Q}{XS_{\mathcal{P}}}\right)^{1+\gamma} K_\iota^{\frac{1+\gamma}{\gamma}} < 0 \tag{56}$$

$$\frac{\partial \Pi}{\partial Q} = \frac{\gamma(1+\gamma)w}{Q}\left(\frac{Q}{XS_{\mathcal{P}}}\right)^{1+\gamma} K_\iota^{\frac{1+\gamma}{\gamma}} > 0 \tag{57}$$

$$\frac{\partial \Pi}{\partial P} = 0 \tag{58}$$

$$\begin{aligned}\frac{\partial \Pi}{\partial K_\iota} &\approx \frac{(1+\gamma)}{\gamma K_\iota}\left(\gamma w\left(\frac{Q}{XS_{\mathcal{P}}}\right)^{1+\gamma} K_\iota^{\frac{1+\gamma}{\gamma}} - \sigma\delta K_\iota^\delta\right)\\ &= \frac{(1+\gamma)}{\gamma K_\iota}\left(\Pi + (1-\delta)\sigma K_\iota^\delta\right) > 0 \end{aligned} \tag{59}$$

Note that for inequalities (54) and (59), we assume that the number of vessels is sufficiently large to ignore dS/dK_ι. For inequality (59), $\delta < 1$ is a sufficient (though not necessary) condition. The comparative statics results follow.