College of Business and Public Policy
UNIVERSITY of ALASKA ANCHORAGE

Department of Economics Working Paper

WP 2013-03

October 2013

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Unraveling the Multiple Margins of Rent Generation from Individual Transferable Quotas☆

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Abstract

Individual transferable quotas (ITQs) induce changes along the both the *extensive* margin—via consolidation of quota among fewer vessels—and the *intensive* margin, as harvesters adjust their behavior to ITQ incentives. We use ITQ introduction in the Bering Sea crab fishery to decompose the sources of rent generation across both margins. We embed an empirically calibrated structural model of the harvesting process into a sector-level model, allowing us to experimentally "unravel" the ITQ treatment. We show that the magnitude and source of rent generation under ITQs critically depends on the manner and degree of rent dissipation before ITQs are implemented.

Keywords: Fisheries, ITQ, rents, production function, intensive margin, Alaska, crab.

☆We thank a number of individuals for helpful comments, including Eli Fenichel, Nick Kuminoff, Ron Felthoven, Brian Garber-Yonts, John Boyce, as well as seminar participants at UC Davis, Arizona State University, University of Calgary, and NAAFE 2011, PERC 2011, and AERE 2012 meetings. Part of this work was completed while Matthew Reimer was a pre-doctoral fellow at the Center for Environmental Economics and Sustainability Policy at Arizona State University. This work was supported by NOAA Award NA08NMF4370485.

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1. Introduction

The most long-standing prediction about ITQs has been that transferable property rights to harvest will induce changes along the *extensive* margin via consolidation of quota among a smaller number of more efficient vessels [1, 2, 3, 4]. This prediction has been substantiated by experience as ITQ programs have universally led to a reduced number of vessels—an outcome consistent with empirical findings of over-capitalized fisheries and pre-ITQ vessels operating under increasing returns to scale. Transferability of harvest rights therefore facilitates the elimination of excess capital, thus addressing the popular depiction of the problem of the commons as "too many boats chasing too few fish."

The literature has also hypothesized that ITQs will induce changes along the *intensive* margin as fishermen adjust their fishing practices and use of variable inputs in response to the altered incentives provided by the security of harvesting rights [1, 5, 6, 7, 8].[1] Yet the precise nature of such changes and their contribution to rent generation has not been clearly articulated in the literature. ITQs prompt discrete changes in the motives of harvesters, away from "racing" for a larger share of the total allowable catch (TAC) and toward maximizing the value of their quota. The literature has hypothesized, somewhat vaguely, that fisheries operations will be less "intensive" relative to "race to fish" conditions, but what does this mean in practice? Which practices are altered after ITQs dampen "race to fish" incentives and how do these contribute to the overall rent generation process?

Distinguishing between consolidation-induced rents and those generated by ITQ incentives is of practical importance for fishery policy evaluation. While most economists advocate ITQs as a means to address the perverse incentives that exist under command and control regulatory institutions, the prospect of introducing ITQs is often met with various degrees of hostility by industry and fishing community members. Previous work [14, 15] suggests that heterogeneous fishermen act antagonistic towards ITQ introduction to protect non-transferable infra-marginal "skill" rents generated under command and

[1] Hypotheses about behavioral changes along the intensive margin initially emerged as limited entry programs began to reveal "capital stuffing" and other evidence of input intensification [9]. Subsequent work has examined the importance to rent dissipation of the elasticity of substitution between regulated and unregulated inputs in two-input models under atomistic behavior [10, 11, 12]. More recent work generalizes to multiple restricted and unrestricted inputs under first-best and open access settings [13].

control regulations. In this case, skilled fishermen may prefer consolidation without ITQ introduction, perhaps through a vessel buyback program. In contrast, fishing community members often worry about the effects of consolidation through concentration of fishery rents among fewer boat owners and the subsequent loss of jobs and economic activity in coastal communities [8, 16, 17, 18, 19]. In this case, coastal communities may prefer an ITQ system that restricts the trading of quotas to limit consolidation. Thus, depending on the bargaining strength of potential ITQ-affected stakeholders, "suboptimal" policies could be adopted in lieu of ITQs [20]. Distinguishing between consolidation-induced rents and those generated by ITQ incentives can therefore shed light on the potential outcomes that may occur under such "second-best" policies.

Unfortunately, separately identifying the contribution of consolidation and incentives to the rent generation process is complicated by the fact that these two sources of rents rarely occur in isolation. Secure harvesting rights are often accompanied by consolidation of the fleet, thereby confounding the two sources of rent generation as actions taken along the extensive and intensive margins interact with each other. As ITQ is consolidated and vessels are reduced along the extensive margin, the average scale of operation increases for remaining vessels, increasing the use of some variable inputs. At the same time, with secure access to a portion of the total quota, each vessel is, ceteris paribus, no longer compelled to intensify effort to compete in the race to fish, reducing the need for some inputs. Separation of the multiple sources of rent generation thus requires an experimental-like setting that can evaluate counterfactual scenarios such as introducing secure harvesting rights without fleet consolidation or vice versa.

In this paper, we use the 2005 introduction of ITQs to the Bering Sea red king crab (RKC) fishery as a platform to separately identify rents arising from consolidation of quota among a smaller number of vessels and those prompted by the security of harvesting rights. We unravel the multiple sources of ITQ rents by embedding a detailed calibrated model of the fishing production process into a sector-level model, with the purpose of simulating controlled counterfactual scenarios. Specifically, we model a limited entry (LE) fishery and an individual (non-tradable) quota (IQ) fishery as two distinct fleet-wide games, with each game differing according to the regulatory setting of the fishery. This provides us with an experiment-like setting that enables the assessment of institutional "treatments" to distinguish between the contribution of consolidation and incentives to the rent generation process under ITQs. In particular, we identify the rents prompted by ITQ incentives as those generated by the movement from an LE to an IQ fishery while holding the number of vessels constant to control for consolidation. Rents generated from consolidation are identified as those rents arising from the removal of vessels from a fishery, holding the institutional setting constant.

Identifying the sources of rent generation requires an understanding of the key margins along which producers are able to respond to a policy change, their technical interrelation (i.e. degree of substitutability), and the extent to which regulatory, economic or technical realities constrain producers' choices across these margins. Generating plausible adjustments in our simulation model therefore requires a more complete *a priori* description of the production process than is typical in most economic analyses. The detailed structural description of fishing production in this paper is designed to capture the context-specific intensive margin decisions available to fishermen immediately following the introduction of ITQs. For instance, the production process of capture fisheries involves the strategic use of gear over time and space in ways that are too subtle to be modeled by simple input-output relationships. Our model of the fishing production process represents the main decisions made by a representative skipper throughout a fishing season with respect to traveling to and from fishing grounds and the process of setting and lifting traps (or pots).[2] We calibrate and parameterize our model using a rich pre- and post-ITQ survey data set from the RKC fishery that includes important choices at the gear deployment and trip level that reveal how fishermen use time and space to optimize profits over the season.[3] Importantly, we provide a model of the production process that is sufficiently structural so as to be invariant to changes in management institutions [24].

Our results provide a detailed and nuanced accounting of the multiple margins of fishing behavior influenced by ITQs, and the consequent sources of rent generation from implementation of secure harvesting rights. We show that the total effect of ITQ introduction is the sum of two competing effects. In particular, ITQ incentives tend to slow down the intensity of harvesting over time and space whereas consolidation tends to

[2]See [21, 22, 23] for examples of other production models for trap-based fisheries.

[3]These data sets consist of confidential skipper interviews conducted by the Alaska Department of Fish and Game (ADF&G) Shellfish Observer Program, annual Economic Data Reports, and ADF&G Fish Tickets. A detailed description of each dataset is included in an online appendix.

act in the opposite direction as fewer boats increase input use to harvest their increased allocations. Our results suggest that the majority of rent generation from ITQ introduction in the RKC fishery stems from the elimination of excess capital and its associated seasonal opportunity cost. More broadly, we find that the degree and components of rent generation from ITQ introduction are determined by the interaction of economic, technological, and biological parameters, and the degree of pre-ITQ over-capitalization. Overall, rent generation and the contribution provided by ITQ incentives depend on the extent to which rents were dissipated along the intensive margin prior to ITQs. In the RKC case, the fishery was dramatically overcapitalized before rationalization; hence the major source of rents was via consolidation rather than along the intensive margin.

2. The Bering Sea RKC fishery

Prior to ITQ adoption, the RKC fishery was a classic example of an extreme "derby." Managed under a limited entry program, the TAC was harvested in 3 days in a frenzy of round-the-clock fishing in which well over 200 catcher vessels pushed crew and gear to their limits (Figure 1). Drastic changes in fishery regulation occurred in 2005 as management attempted to reduce the over-capitalized fleet, extend the season, increase safety, and reduce economic and biological waste. License holders were allocated quota shares, revocable privileges that granted owners an annual allocation of a specific portion of the annual TAC. Once the annual TAC is set, quota share owners are allocated an individual fishing quota that permits them to harvest a specific amount of pounds of crab. Vessels can enter or exit the fishery by purchasing or selling their quota shares and short-run arrangements are made possible by the annual leasing of individual fishing quota.[4]

The immediate result of ITQ introduction was a reduction in the fleet size to ap-

[4]Rationalization also allocated individual processing quota (IPQ) to processors, along with ITQ-IPQ matching requirements and regional landing requirements to 90% of ITQ shares. IPQs were designed to preserve existing delivery relationships among vessels and processing plants and communities with the purpose of protecting the investments of processors and limiting impacts to fishery-dependent communities. While the introduction of both ITQs and IPQs arguably changed the nature of the relationship between harvesters and processors, we focus solely on the impact of ITQs on production decisions of harvesters. See [25, 26] for more on the potential impacts of IPQs.

proximately one-third of its pre-derby size (Figure 1), a threefold increase in the typical number of fishing days per season [19], and an overall increase in the scale of operation for the vessels remaining in the fishery (Figure 2a). In addition to ITQ introduction in 2005, management also relaxed historical limitations on the number of pots that could be used to harvest crab. Figure 2b displays the number of registered pots for each season by vessel class for only those vessels that remained in the fishery after rationalization.[5] The upper bound on pot usage was based on the annual TAC and differentiated by vessel size and was often binding in the pre-rationalization years. While there is some indication that some vessels tend to use more pots after rationalization, the overall trend at the median has been to decrease the number of pots.

To investigate the changes in the intensive use of production inputs after the introduction of ITQs, we use an unbalanced panel of dockside or onboard confidential skipper interviews. These interviews obtain information on each string of pots that was deployed throughout a trip, including the number of pots deployed, the average soak time of the pots, the number of crab caught in a string, the day the pots were retrieved, the general location of pot deployment, the beginning and end date of the trip, and a sample of the catch to determine the average weight of crab. Limiting our analysis to vessels that participated in the fishery both before and after rationalization, a significant increase in the average soak time for a string of pots and a large decrease in the number of pot retrievals per fishing day occurred with rationalization, along with substantial increases in variability within and across vessel classes (Figure 3). Median soak time increased from around one to two days and is fairly stable before and after rationalization while median pot retrievals per day increased as the derby intensified and decreased by approximately 40 pots per day after rationalization.[6]

Although the increase in soak time and decrease in pot lifts per fishing day after rationalization are clear, their causes are less evident.[7] Are the changes due to altered

[5]Data on the number of pots registered for a given season comes from the ADF&G Commercial Fisheries Division.

[6]See [27] for a comprehensive review of all rationalized Alaskan crab fisheries fiver years after ITQs were implemented.

[7]Median regressions of soak time and pot lifts per days controlling for temperature, wind speed, ex-vessel prices, vessel length, and seasonal-gear fixed effects support the general findings in Figure 3. More information regarding the median regressions is included in an online appendix

incentives under ITQs, or are they due to the consolidation of quota upon fewer vessels?[8] In other words, would we observe the same changes in the intensive use of production inputs in the RKC fishery had management simply restricted fleet size and fishery employment to one-third of its pre-rationalization size? Moreover, did distinct changes along the intensive margin result in substantial rent generation? If so, to what extent can rent generation be attributed to ITQ incentive effects or consolidation effects? In the absence of observing incentive and consolidation effects in isolation, we use the data sources drawn upon in this descriptive analysis to calibrate a structural model of a representative vessel operation that is capable of depicting harvester behavior under alternative forms of fishery management.

3. Model of the harvesting production process

On first glance, crab fishing appears relatively simple and even almost primitive, using gear that is deployed, left to soak, and then retrieved. This simplistic assessment belies the many important decisions that a fisherman must make throughout a fishing trip: the number of pots to deploy, the areas in which pots are deployed, the distance between pots, and the speed of travel between pots. Production decisions such as these are not typical in most conventional production processes and yet are the fundamental short-run decision variables for fishermen.

Our model depicts the process of fishing a uniformly distributed stationary crab population, using pots that are repeatedly set and retrieved. Our depiction of the crab fishing process can be thought of as managing a string of pots post-search, i.e. once fishermen have found a desired fishing location.[9] We measure time continuously, but associate different divisions of time consisting with various decisions. A season generally involves multiple trips, each representative of multiple days of more or less continuous pot lift activity. The model captures the main decisions made by a skipper and crew

[8]It is also possible that the post-ITQ changes in fishing practices are due to the relaxation of pot limits after 2005. The lack of a dramatic increase in registered pots after the pot limits were lifted, however, suggests that this is not the case.

[9]Our model of the crab fishing process can also be thought of as the second stage of a two-stage dynamic game, where in the first stage, harvesters search for an adequate fishing location, and in the second stage, harvesters manage a string of pots with the purpose of extracting the discovered crab population.

with respect to traveling to and from fishing grounds, managing a string of pots, and the process of setting and lifting pots. These decisions involve the following endogenous decision variables:

S = soak time for a single pot (days)

N = number of pots in a string (pots/string)

d = distance between pots (nautical miles (nm))

v = velocity of travel between pots (nm/day)

τ^h = pot handling time (days/pot)

T^f = fishing days in a trip (days/trip)

t = number of trips during the season

P^L = total pots lifted during the season (pots/season)

We assume that skippers distribute a string of uniformly spaced pots around their chosen fishing grounds in a "working circle" such that once a vessel has worked its way around the entire string, retrieving, baiting and resetting each pot, the first pot is ready to pull to start the process over again.[10] Each baited pot within a string attracts and traps crab after being left to soak, and has the capacity to trap multiple crabs.[11] Vessels are assumed to use one string of pots per trip, but the number of pots per string N is a choice variable. In addition, skippers are assumed to choose the distance d between pots and the velocity v with which the vessels travel between pots—both of which affect the rate at which pots are pulled and the length of time pots are left to soak in the water.

[10]While posed as an assumption, the continuous nature of pulling and setting pots, without any idle time, is due to the convexity of the velocity cost function (Section 3.2) and the lack of incorporation of any explicit benefits for idle time in our model.

[11]Note that a "string" of pots in the RKC fishery is not an actual physical string connecting pots; rather, it represents a collection of pots that are more or less continuously placed in the water one after the other. Other assumptions about the shape of a string of pots, such as a line, can also be used, but require additional variables such as time spent traveling between the first and last pot. Thus, we choose to use a circle for the sake of parsimony.

We define pot handling time τ^h as the time spent retrieving, baiting, and setting a pot τ^s plus the time spent traveling to the next pot. Given our assumption of a stationary, uniformly distributed crab population, the most efficient use of time involves setting each pot sequentially in the working circle. This results in the following relationship for pot handling time:

$$\tau^h = \tau^s + \frac{d}{v}. \tag{1}$$

where we have assumed that τ^s is exogenous for simplicity. Furthermore, our "working circle" assumption implies that soak time must be equal to the number of pots per string times the handling time per pot,

$$S = \tau^h N, \tag{2}$$

where we have assumed, for simplicity, that the first and last pot lifts take the same time as intermediate pot lifts and that any time spent traveling to and from the fishing grounds while pots are in the water does not contribute to soak time.

In principle, skippers can choose the number of days spent fishing during a trip T^f, the time spent traveling to and from the fishing grounds for each trip T^t, and the number of fishing trips t undertaken during the course of a season. Ignoring environmental factors, such as weather and sea conditions, or contractual agreements between vessels and processors (e.g. predetermined delivery dates), we would expect that a skipper would stay at sea until the vessel's hold capacity H was binding, the seasonal TAC had been met, or catch deterioration became a significant concern. This gives us the following relationship for a season of length T:

$$(T^t + T^f)t = T, \tag{3}$$

where we assume, for simplicity, that T^f is the same for each trip and that T^t is exogenous.

The variables P^L and P^S indicate the number of times pots (not necessarily unique pots) are lifted and set over the entire season.[12] We assume that pots are lifted/set continuously throughout all fishing days for a trip until the end of the season. Furthermore, we

[12] We differentiate between pots set P^S and pots lifted P^L to account for the fact that the first time pots are set, vessels are not simultaneously obtaining any production from lifting previously soaked pots. This accounts for the implicit cost of setting a large number of pots: it requires more time to get around the first string of pots, delaying the actual crab accumulation process, which is what determines a vessel's cumulative harvest.

assume that once the N pots are distributed in the working circle for the first time, they are left at their original spatial position until the end of the season, even while a vessel travels between shore and the fishing grounds. Thus, we have the following relationships:

$$\tau^h P^S = T^f t \tag{4}$$

$$P^L = P^S - N, \tag{5}$$

where we have ignored any pot lifts that occur after the season is ended. Equation (4) says that the handling time per pot lift multiplied by the total pots set during the season will equal the total time spent fishing during a season.

Using the relations and assumptions listed above, all decisions made by a skipper and crew throughout a trip can essentially be reduced to decisions about the number of pots per string N, the distance between pots d, the speed at which the vessel travels v, and the number of trips t taken during the season. Thus, we have the following relationships for soak time per pot S, handling time per pot τ^h, pots lifted per season P^L, pots set per season P^S, and time spent fishing during a trip T^f:

$$\begin{aligned} S(d,v,N) &= N\left(\tau^s + \frac{d}{v}\right) \\ \tau^h(d,v) &= \tau^s + \frac{d}{v} \\ T^f(t,T) &= \frac{T}{t} - T^t \\ P^S(d,v,t,T) &= \frac{T^f(t,T)}{\tau^h(d,v)}t \\ P^L(d,v,N,t,T) &= P^S(d,v,t,T) - N \end{aligned} \tag{6}$$

The relationships in (6) expose the intricate linkages between time and space in the harvesting production process. For example, decreasing the distance traveled between pots not only affects the use of production inputs over space, but also affects the use of production inputs over time through soak time and handling time.

3.1. Seasonal production function

The amount of crab caught throughout a season revolves around the productivity of each pot used by a vessel. We model a vessel's catch per pot as a saturating function of soak time that is sensitive to the density of pots surrounding it. In particular, we assume that catch per pot follows a von-Bertanlanffy type equation [21, 28] that has been modified to account for the effects of congestion. Namely, we model catch per pot $g(\cdot)$ to be

$$g(d, v, N, N_{-i}) = \delta(d, N, N_{-i})D\left(1 - e^{-\gamma S(d,v,N)}\right) \tag{7}$$

where $\delta(\cdot)$ represents an "inverse congestion" index which approaches 0 with high levels of congestion and approaches 1 when there is little congestion, D represents a "congestion-free" asymptotic catch per pot, and γ represents the rate at which the asymptotic catch is reached. The inverse congestion index (henceforth congestion index) is modeled to be a function of the density of one's own pots within a working circle (own-pot congestion) and the total number of pots used by other fishery participants (cross-pot congestion) so that there is a production/congestion externality across vessels. Specifically, we model the congestion index to be the product of two generalized logistic functions,

$$\delta(d, N, N_{-i}) = \left[\frac{1}{\left(1 + exp\{\lambda^d(\frac{4\pi}{Nd^2} - m^d)\}\right)}\right]\left[\frac{1}{(1 + exp\{\lambda^N(N_{-i} - m^N)\})}\right] \tag{8}$$

where $4\pi/Nd^2$ is the number of own pots per unit area of the working circle and N_{-i} is the number of pots supplied by all other vessels in the fishery. The parameters λ^d and λ^N jointly determine the rate at which the congestion index approaches 0, while the parameters m^d and m^N are the levels of own pot density and pots in the fishery, respectively, at which the decline in the congestion index is at its greatest.

The sigmoid-shaped own-pot congestion index curve is consistent with two competing pot spacing effects that influence catch per pot: a high density of pots, and thus bait, will attract more crabs but each pot will catch a smaller fraction of the attracted crab population. As the area per pot approaches zero (i.e. pots are essentially stacked on top of each other), each pot will attract only an infinitesimally small fraction of the local crab population so that catch per pot approaches zero. At the other end of the spectrum, as the area dedicated to each pot approaches infinity, each pot catches a larger fraction of the crab population, but less crab are attracted to the pot so that catch per pot asymptotes to its congestion-free level of accumulation.

The cross-pot congestion index curve can be interpreted as a congestion externality across vessels, where the effect of competitors' pots through congestion is isomorphic to the effect of one's own pots on catch per pot. With a small number of pots spread across the fishing grounds, the existence of other pots in the water will have little effect on an individual vessel's production from a string of pots and the congestion index approaches one. As the number of pots in the fishery increases, the degree of encroachment on an individual vessel's string increases, attracting crabs away from a vessel's own pots, forcing the congestion index to approach zero as the number of pots in the water approaches infinity. Thus, the production process of an individual harvester is intricately linked to the choices and number of other vessels in the fishery.[13]

We can write a representative vessel's seasonal production function $F(\cdot)$ as the number of pots lifted per season times catch per pot:

$$F(d, v, N, t, T, N_{-i}) = P^L(d, v, N, t, T) \times g(d, v, N, N_{-i}). \tag{9}$$

Thus, the amount of crab caught in a season depends on a complex relationship between the spacing of pots, travel velocity, the number of pots in a string, the number of trips in a season, and the production decisions of all other vessels in the fishery. Of course, the amount of crab sold in a season will also depend on how/if crab deteriorate in the live tank as harvesters are at sea. Rather than explicitly modeling the process by which crab deteriorate, we let the proportion of crab that is alive at delivery $\rho(\cdot)$ be a decreasing function of time spent fishing and traveling to shore during a trip

$$\rho(t, T) = 1 - \theta \left[T^f(t, T) + \frac{1}{2} T^t \right]^\sigma, \tag{10}$$

where $\sigma > 1$ and $\theta > 0$, guaranteeing that $\rho(\cdot)$ is concave.

3.2. Seasonal costs

We define the variable costs per season to be

$$C(d, v, N, t, T) = c^u + c^o + c^t t, \tag{11}$$

where cost per season is divided into three components:[14] usage costs c^u, which consist of the rental costs of committing N pots and a vessel to the fishery; operating costs c^o, which consist of everyday fishing operations, such as baiting pots, traveling between

[13] Note that our notion of own-pot congestion is consistent with the trap-based production model developed by Gates [23], while our notion of cross-pot congestion is consistent with the fleet wide trap congestion found in Holland's [22] investigation of the Maine lobster fishery.

[14] Our method of breaking apart costs in such a way as to capture the primal relationships between production inputs is similar to the decomposition of vessel expenditures in [13].

pots, and the cost of labor provisions; and travel costs $c^t t$, which are the costs incurred from traveling to and from the fishing grounds throughout the season. In particular, let the rental cost of committing a single pot and a vessel to the fishery be c^N and r, respectively, so that usage costs are $c^u = c^N N + r$. In addition, we assume that operating costs during the season consist of the direct costs of setting/lifting pots c^p, the steaming cost per pot—as a function of fuel consumption—multiplied by the number of pots pulled throughout the season, and daily labor costs c^ℓ times the length of the season T. That is,

$$
\begin{aligned}
c^o &= P^S(d,v,t,T)\left(\left[\frac{\textit{set cost}}{\textit{pot}}\right] + \left[\frac{\textit{steam cost}}{\textit{pot}}\right]\right) + c^\ell T \\
&= P^S(d,v,t,T)\left(c^p + \rho^f \phi(d,v)\right) + c^\ell T, \qquad (12)
\end{aligned}
$$

where ρ^f represents the price of fuel. Importantly, crew labor in the RKC fishery typically receives a share of revenues after certain costs have been deducted [19] so that c^ℓ is interpreted as daily labor provisions, such as food, rather than as daily crew remuneration.[15]

To capture the technological realities of traveling between pots, we model fuel consumption per pot $\phi(\cdot)$ as a function of velocity and distance:

$$
\phi(d,v) = \Theta v^\beta d, \qquad (13)
$$

so that fuel consumption per pot is linear in the distance traveled between pots and convex in velocity (i.e. $\beta > 1$). In addition, to represent the limitations of vessel technology, we assume vessels can only travel up to a maximum velocity of $\bar{v}$. Importantly, Θ, β, and $\bar{v}$ are fixed technological parameters (in the short-run) that are influenced by vessel characteristics such as length, horsepower, tonnage, etc. Furthermore, these technological parameters completely determine travel costs c^t if we assume vessels always travel the same distance to and from shore at a constant speed, both of which we take as given for simplicity.

Putting all costs together, we have the following expression for variable costs per trip

[15] In general, not accounting for the crew share can lead to inaccurate representation of some aspects of commercial fishing behavior [29]. In our model, we interpret c^ℓ as a daily labor provisioning cost, which allows us to calibrate the model's labor costs to be commensurate with actual crew shares in the RKC fishery.

as a function of d, N, v, and t:

$$C(d,v,N,t,T) = c^N N + P^S(d,v,t,T)\left(c^p + \rho^f \phi(d,v)\right) + c^\ell T + c^t t + r. \tag{14}$$

Thus, seasonal costs are linear in the number of pots set and depend on a complex relationship between the distance traveled between pots, travel velocity, and the number of trips per season.

4. Sector-level model

We capture the decision-making environment for each counterfactual scenario as a static game of complete information with an endogenous season length $T(\cdot)$ that is determined by the actions of all players.[16] For tractability, we follow standard practice and ignore heterogeneity to focus on a model of the representative decision maker. We further assume that the number of harvesters η is determined exogenously. In each game, harvesters choose an action at the beginning of the season from their feasible strategy set, which consists of a number of pots $N > 0$, a travel velocity $\bar{v} > v > 0$, and a distance between pots $d > 0$, that are all constant over the entire season, and the number of trips $t \in \{1, 2, 3, ...\}$ they will make during the season. Players are assumed to choose actions to maximize a payoff function Π—their seasonal profits—for any given strategy of their rivals, keeping in mind that the amount of crab caught during a trip cannot be greater than the vessel's hold capacity H:

$$\begin{aligned} \max_{d,v,N,t} \quad & \Pi = \bar{\rho} \times \rho(t, T(\cdot)) \times F(d,v,N,t,T(\cdot),N_{-i}) - C(d,v,N,t,T(\cdot)) \\ \text{subject to} \quad & \frac{F(d,v,N,t,T(\cdot),N_{-i})}{t} \leq H, \end{aligned} \tag{15}$$

[16]Due to the lack of within-season stock or ex-vessel price dynamics, our model can also be interpreted as a dynamic game with commitment or a dynamic game in which there is no new information conveyed over the course of a season, both of which reduce to a static game. Relaxing the stationary stock or ex-vessel price assumptions would require—at minimum—the computation of an open-loop Nash equilibrium whereby harvesters commit to a time path for each choice variable at the beginning of the season [30]. Relaxing the complete information assumption would require the computation of a closed-loop Markov-Perfect Nash equilibrium whereby harvesters form state-dependent strategies at each period of time and choose actions as information is revealed throughout the season. Relaxing any of these assumptions would increase our computational burden significantly, especially with an endogenously determined time horizon [31].

where $\bar{\rho}$ is the ex-vessel price of crab.[17] While vessel owners receive a share of profits, the objective function in (15) is not weighted by the maximizer's share of seasonal profits. Since the costs we account for in equation (14) are typically deducted from revenues *prior* to calculating shares, the objective function for the decision maker is nothing more than a monotonic transformation of (15). This convenience allows us to be ambiguous about whether the objective function in (15) belongs to the vessel owner, the skipper, or the crew, without changing our behavioral results. However, this ambiguity means that the fishery rents in our model are measured $before$ the payment of labor.

The normal-form representation above implies that each counterfactual scenario is a symmetric game: all players have the same strategy set and payoff functions so that the payoff to playing a given strategy depends only on the strategies being played, not on who plays them. Thus, we use a symmetric pure-strategy Nash equilibrium as the outcome to our sector-level model. We solve the model for two different institutional settings: an individual (non-tradable) quota (IQ) fishery—whereby harvesters are allocated a secure and fixed share of a TAC—and a limited entry (LE) fishery—whereby harvesters compete for a share of a common pool TAC. The two fisheries differ only in assumptions about the determination of season length. We assume that season lengths are determined to ensure that a biologically determined TAC is not exceeded.

If the fishery is regulated by IQs, then an individual vessel?s season length is simply modeled as the length of time it takes to reach its individual quota Q. Thus, using catch per season $F(\cdot)$ in equation (9) combined with the identities in (6), each harvester in the IQ fishery has the following endogenously determined season length T^{ITQ}:

$$\begin{aligned} & Q = F(d, v, N, t, T^{ITQ}) \\ \implies \quad & T^{ITQ} = \left[\frac{Q}{g(d, v, N, N_{-i})} + N \right] \tau^h(d, v) + T^t t. \end{aligned} \tag{16}$$

We assume that each identical harvester is allocated the same portion of the TAC so that a harvester?s fixed quota is $Q = TAC/\eta$ [31, 35]. Note that even though harvesters are

[17] Several examples in the literature have shown that ex-vessel prices may be affected by ITQs through changes in the temporal distribution of industry effort [22, 31, 32] and/or changes in non-competitive pricing structures between harvesters and processors [25, 33, 34]. For the sake of simplicity, we assume that ex-vessel price is exogenous, noting that ex-vessel price for Alaskan crab is often set by arbitration prior to the beginning of the season [27, 33]. ITQ- and IPQ-induced changes in bilateral negotiating power between RKC harvesters and processors is beyond the scope of this paper.

guaranteed a share of the TAC, the resulting game between harvesters is not trivial due to the production externality that exists between vessels, which affects an individual's season length through a congestion effect on catch per pot.[18]

If the fishery is managed by an LE program, then season length is modeled as the length of time it takes for the entire fleet to reach the TAC. Assuming that all other players choose the same actions and letting the subscript $-i$ represent the common actions of other players, then an individual harvester's season length is endogenously determined by

$$\begin{aligned} &TAC = F(d, v, N, t, T^{LE}) + (\eta - 1)F(d_{-i}, v_{-i}, N_{-i}, t_{-i}, T^{LE}) \\ \implies \quad &T^{LE} = \frac{TAC + \left(\frac{T^t}{\tau^h(\cdot)}t + N\right) g(\cdot) + (\eta - 1)\left(\frac{T^t}{\tau}t_{-i} + N_{-i}\right) g_{-i}}{\frac{g(\cdot)}{\tau^h(\cdot)} + (\eta - 1)\frac{g_{-i}}{\tau^h_{-i}}}, \end{aligned} \tag{17}$$

where we use the definition of $F(\cdot)$ in equation (9) and substitute in the various identities in (6) to obtain equation (17). The season length for the LE fishery differs from that of the ITQ fishery due to the fact that the LE harvestable stock is a common property resource. That is, unlike the ITQ fishery, harvesters in the LE fishery are not guaranteed a certain portion of the TAC at the beginning of the season. Thus, any actions that increase the seasonal production of one player reduces the time in which another player has to harvest crab before the TAC is met.

5. Hypothetical experimental design

We use the sector-level model within a hypothetical experimental setting to view the changes in production decisions and rents induced by ITQs as the outcome of two simultaneous treatments—changes arising from consolidation of quota among a smaller number of vessels (consolidation effects) and changes prompted by the security of harvesting rights (incentive effects). The total rents generated from introducing ITQs are assumed to be the rents induced by a movement from an LE fishery to an IQ fishery with a simultaneous transferability-induced reduction in the number of vessels η. Rents generated from the incentive effect are identified by the movement from an LE fishery to an IQ fishery with

[18] In general, ITQs are not capable of dealing with in-season congestion and stock externalities, resulting in ITQ fishery rents that are less than those that could be achieved under sole ownership [22, 30, 31, 35, 36].

the same number of vessels so that consolidation remains constant. Rents generated from the consolidation effects are identified as those rents generated by removing vessels from a fishery, holding the institutional setting (i.e. IQ or LE) constant. Given the "representative agent" nature of our model, the incentive and consolidation effects of the scenarios we examine are predicated on the simplifying assumption that the pre-ITQ fleet is homogeneous. This assumption eases the computational burden and is useful for establishing baseline intuition in a relatively simple case. However, it does prevent us from modeling the gains from transferability due to the gravitation of quota to more efficient vessels. Consolidation rents are thus restricted to the elimination of excess capital and average cost savings from increased scale of operation. As such, our estimates of the gains from consolidation will serve as a lower bound for a more heterogeneous fishery.

Formally, LE_{232} in Figure 4 denotes an LE fishery with 232 vessels—representing the RKC fishery prior to ITQs—and serves as the baseline in our hypothetical experiment. The total effects of introducing ITQs (IQ_{78} - LE_{232}) are captured by Treatment A, which applies IQs to LE_{232} with a simultaneous reduction of the fleet from 232 to 78 vessels.[19] The total effects of ITQs are separated into consolidation effects and incentive effects through two sets of successive treatments: (1) treatments B and C, and (2) treatments D and E in Figure 4. The first set of treatments applies IQs to LE_{232}, which prohibits quota transfers so there is no exit from the fishery (treatment B), followed by an exogenous consolidation of the IQ fishery from 232 to 78 vessels (treatment C). The second set of treatments reduces the number of vessels in the LE fishery from 232 to 78, as in a vessel buyback program (treatment D), followed by an introduction of IQs to LE_{78} (treatment E). Thus, the two sets of treatments differ only by whether ITQs are introduced before or after consolidation. The effects of treatments B (ITQ_{232} - LE_{232}) and E (ITQ_{78} - LE_{78}) capture the incentive effect by holding consolidation constant, while the effects of treatments C (ITQ_{78} - ITQ_{232}) and D (LE_{78} - LE_{232}) capture the consolidation effect by holding the regulatory institution constant. Note that even though the total effects B + C and D + E are both equal to the effects of treatment A, the sequencing of the

[19] Because we do not model the actual consolidation process after ITQ implementation, we choose the number of vessels to be the actual number of vessels in the fishery in 2004 and 2006 respectively. We compare the 2004 LE fishery with the 2006 ITQ fishery to allow for a short adjustment period as the RKC fishery adjusted to the new management institutions.

treatments matter for their effects so that C$\neq$D and B$\neq$E.[20]

6. Discussion

Given the complicated nature of the harvesting production process, an analytical solution to the maximization problem in (15) cannot be derived for either the LE or ITQ counterfactuals. Thus, we use numerical methods to obtain individual best responses and the SNE. Since we treat the number of trips t as an integer, the maximization problem in (15) is a mixed integer nonlinear programming problem that is solved in MATLAB. The payoff function in equation (15) is not quasiconcave so that the resulting non-convexity of the strategy set does not guarantee the existence of a SNE for all possible combinations of model parameters. However, careful calibration of the model to the 2004 conditions of the RKC fishery results in the existence of a SNE for the range of counterfactual scenarios we consider. A subset of model parameters are calibrated through the use of information derived from informal discussions with skippers and parameter estimates from previously described data. The values of the remaining "free" parameters are chosen to minimize the proportional distance between certain model predictions from the LE fishery and their median counterparts in the data for the 2004 season.[21]

The actual medians used as calibration points and their corresponding final model predictions can be seen in columns (1) and (4) of Table 1, respectively.[22] As a validation check for our behavioral model and calibration, we simulate an ITQ fishery under 2006 conditions and compare the percentage difference in the actual medians between 2006 and 2004 (column 3) with the percentage difference in model predictions between 2006 and 2004 (column 6). For the ITQ fishery simulation, we use our calibrated parameters and adjust only the ex-vessel price and fuel price to mimic the conditions of the 2006 RKC

[20]The path independence of the bundled ITQ treatment (B+C=D+E) need not hold in a fishery populated by heterogeneous vessels. For instance, a large-scale initial buyout followed by the introduction of ITQs may lead to a different composition and number of vessels than if ITQs were introduced before fleet consolidation, with consolidation managed by market transfers.

[21]Details about the calibration process, the data used for calibration, our numerical methods, and the parameter values used in our simulations are included in an online appendix.

[22]In addition to these calibration points, we also calibrated to the median fuel consumption per harvested crab. However, due to the North Pacific Fishery Management Council guidelines for the reporting of these data (described in the appendix), we do not report these numbers in Table 1.

fishery.[23] Despite the complex nature of the harvesting process, our simple calibrated model does quite well at predicting both the median fishery outcomes and the relative behavioral changes witnessed in the data.[24]

The results from each of the treatments in our hypothetical experiment are presented in Table 2, where the use of production inputs has been grouped according to the use of time or space. The total effects of ITQ introduction—represented by the black bars in Figure 5—support the traditional hypothesis that fisheries operations will be less "intensive" relative to race to fish conditions, across both time and space. This is reflected through decreases in both the velocity traveled and pot lifts per day, indicating an overall decrease in temporal intensity, along with an increase in spacing between fewer pots, indicating an overall decrease in spatial intensity. Furthermore, increased pot spacing in conjunction with fewer pots greatly reduces congestion levels and productivity—measured in both catch per pot and catch per day. Overall, the total effects of ITQ introduction result in a decrease of 64% in the average variable cost and an increase of 16% in fishery rents.[25]

Figure 5 also depicts the separation of the total effects of ITQ introduction into incentive and consolidation effects, where column (a) presents the effects from introducing IQs before consolidation (treatments B and C) while column (b) presents the effects of consolidation before introducing IQs (treatments D and E). Consolidation alone appears to have the effect of intensifying harvester behavior in both the temporal and spatial dimensions; increasing the scale of their operations induces harvesters to pull pots faster to avoid product deterioration. In contrast, incentive effects in isolation seem to diminish the intensity of input use over time and space; suppressing the "race-to-fish" allows

[23]Ex-vessel prices in 2006 were nearly one-third lower than in 2004, while fuel prices were nearly fifty percent higher. The TACs for the 2004 and 2006 seasons were nearly identical; as such, the TAC was not adjusted for the 2006 ITQ fishery simulation.

[24]While our validation exercise is useful for evaluating whether our model performs reasonably well at predicting "out-of-sample," our predictions in Table 1 do not account for any changes in input usage that may arise from the gravitation of quota to more efficient vessels. Thus, we do not expect our predicted changes in input usage to perfectly mimic those experienced in the actual transition to ITQs in the RKC fishery.

[25]We define average variable costs as the seasonal cost of production (14) minus the seasonal rental cost of a vessel r, divided by the number of harvested crab within a season.

harvesters to decrease their velocity and slow their pot-turning rate without the risk of losing a share of the TAC to their competitors. Thus, isolating the incentive and consolidation effects from ITQ introduction reveals that the total effect of ITQs on input usage is the sum of two competing effects. The conventional story of less intensive input use under ITQs therefore hinges on the incentive effect dominating the intensifying effects of consolidation, as demonstrated here by the RKC fishery.

It is clear from Figure 5 that the magnitude of the consolidation and incentive effects depends on whether consolidation is introduced before or after IQs. This distinction lies in the different ways in which rents can initially be dissipated. For instance, a major source of initial rent dissipation stems from the effects of congestion resulting from a large number of pots placed in the fishing grounds. This occurs from a lack of incentive effects as each vessel in the fishery is induced to use more pots, and from over-capitalization with a larger number of vessels to spread pots over the fishing grounds. Thus, both the incentive and consolidation effects in treatments B and D have the capabilities of generating rents through congestion alleviation—despite rents being initially dissipated through congestion in fundamentally different ways. Notably, this means that rents from alleviating congestion are already realized before treatments C and E take place so that their role in generating rents and improving productivity are relatively smaller than their respective counterpart treatments. More generally, this demonstrates that the combination of both a large number of vessels and lack of property rights can cause congestion in a fishery, not just the number of vessels itself.

The disposition of consolidation also takes on different forms depending on the nature in which rents are initially dissipated. For example, simulations that consider treatment C to be continuous along the interval between 78 and 232 vessels show that spatial and temporal effort intensify as vessels are successively eliminated from the IQ fishery.[26] As more quota is stacked upon remaining vessels, harvesters in the IQ fishery are induced to pull pots faster to avoid product deterioration. Eventually, IQ vessels are prompted to incur the fixed cost of spreading production over multiple trips—at which point spatial and temporal effort immediately relax.[27] In contrast, similar simulations for treatment

[26]Additional details concerning our consideration of treatments C and D as continuous along the interval between 78 and 232 vessels are included in an online appendix.

[27]Precisely, vessels in the ITQ fishery transition to two trips when there are 158 vessels remaining in

D show that LE harvesters are not persuaded to incur the cost of an additional trip until the hold capacity constraint is reached—even though they would collectively be better off from making an earlier transition to reduce the amount of crab deterioration that occurs from longer trips. Moreover, LE harvesters continue to lift pots at an ever-increasing rate once the transition to two trips is eventually made. Thus, the effects of consolidation depend upon the manner in which those rents are initially dissipated. In this case, harvesters from each respective fishery are competing for two fundamentally different sources of rents. Harvesters from the LE fishery are racing against each other for shares of the TAC so that transitioning to a second trip means nothing more than an additional fixed cost. In contrast, harvesters from the IQ fishery are racing against deteriorating crab so that once a harvester?s quota is divided between two trips, the fishing pace can slow down again.

Notwithstanding their contrasting effects on input usage, both ITQ incentives and consolidation result in average variable cost savings and higher fishery rents. Reducing the intensity of input use under ITQ incentives results in lower per-unit variable costs, while consolidating quota on fewer vessels allows harvesters to exploit scale economies that arise because of indivisibilities, such as travel costs c_t and pots. Despite these substantial cost savings, Figure 5 demonstrates that total rents generated from ITQs are relatively small in the RKC fishery. Moreover, our results suggest that the majority of rent generation in the RKC fishery stems from changes along the extensive margin as quota is consolidated onto fewer vessels.

One explanation for the relatively small amount of rent generation from ITQs is that the RKC fishery was already generating substantial aggregate rents under limited entry regulations (Table 2).[28] This result is perhaps surprising since a lack of secure harvesting rights is typically associated with the dissipation of fishery rents [37]. As has been demonstrated by [10] and [12], however, the extent of rent dissipation can be limited if the use of some inputs to the production process is restricted and the ability to substitute between restricted and unrestricted inputs is imperfect. In our case, the key restrictions are the limit on the number of vessels in the fishery and the technological

the fishery.

[28]Specifically, rents in the LE_{232} fishery are roughly 95% of the rents that would be generated if all 232 vessels acted collectively to maximize short-run fishery profits.

constraint on velocity. In particular, for both the LE_{232} and LE_{78} fisheries, maximum velocity ($\bar{v} = 12.5$ knots) is binding and prevents rent dissipation in the limited entry fishery. To illustrate this phenomenon, Figure 6 presents the SNE outcomes for the LE_{78} fishery as the maximum velocity constraint $\bar{v}$ is relaxes, relative to a baseline LE_{78} fishery with $\bar{v} = 12.5$ knots. As the maximum velocity constraint is successively relaxed, the "race for fish" intensifies in the LE fishery; harvesters are induced to travel faster ($\bar{v}$ is always binding) in an attempt to lift pots faster and increase their share of the TAC, resulting in higher average variable costs and lower fishery rents. Thus, a technological constraint on traveling velocity limits the extent to which rents are initially dissipated along the intensive margin, thereby relegating incentive effects to a secondary role in the rent generation process.[29] Such a phenomenon is not likely to persist in the long run, however, as we would expect harvesters to adopt new technology and practices that relax the velocity constraint to gain an advantage over one's competitors, thereby intensifying the race to fish and further dissipating rents along the intensive margin.[30]

The relatively dominant role of consolidation in ITQ rent generation can further be explained by the overcapitalized nature of the RKC fishery prior to rationalization. Consolidation rents can be decomposed into two additional sources: rents stemming from removing excess capital and its associated seasonal opportunity cost r; and all other rents proceeding from consolidation, such as scale economies and congestion alleviation. Using this decomposition, it follows that 65% of ITQ-induced rents stem from eliminating excess capital and its associated opportunity cost. While capacity reduction is often an intended consequence of rationalization, this example provides another illustration of how the composition of ITQ- induced rents hinges on the nature in which rents are initially dissipated.

[29]This result was highlighted in interviews with skippers as we began to conduct this analysis. When queried about the most dramatic changes in fishing practices, skippers often cited the leisurely pace in pot handling behavior after ITQs (described as "idling" the vessel from pot to pot) compared with the derby fishery (described as "pedal to the metal" from pot to pot).

[30]Simulations from the LE_{78} fishery that successively relax the maximum velocity constraint (Figure 6) produce a positive and increasing shadow value of velocity—defined here as an individual harvester's maximum willingness to pay for an "infinitesimally" small increase in their own maximum velocity, holding the actions of all other players at their SNE values—indicating that a harvester's best response would be to increase their velocity if they were technological capable.

To explore this idea further, we investigate ITQ rent generation in a fishery with a greater degree of initial rent dissipation along the intensive margin. In particular, we conduct the simulations in Figure 4 using increased fuel prices to induce additional rent dissipation under limited entry regulations (Figure 7). Despite the increased cost of traveling velocity, the examined fuel prices are not sufficiently large to deter vessels from traveling at their maximum speed under limited entry, thereby amplifying pre-ITQ rent dissipation.[31] In contrast, vessels in the ITQ fisheries steadily reduce their velocity as fuel prices rise, substituting towards a larger number of pots and spreading production over more fishing days. The result is a measured increase in the total effects of ITQs as fuel prices grow, moving from a 16% increase in fishery rents when ρ^f=1.9 to a 37% increase when ρ^f =10.[32]

Figure 7 also decomposes the total effects of ITQs into incentive and consolidation effects—which are further subdivided into rents generated by eliminating excessive vessel rental costs r and all other remaining rents from consolidation (as above). Similar to Figure 5, it is clear that the majority of rents under lower fuel prices tend to occur from consolidation with relatively little contribution from ITQ incentives. However, this trend reverses as fuel prices rise, with incentive effects increasing in their importance to rent generation—the extent to which depends upon whether ITQs are introduced before consolidation or vice versa. Importantly, the contribution of incentive effects to ITQ rent generation increases as pre-ITQ rents are dissipated along the intensive margin. More generally, the source of new rents (incentives or consolidation) depends upon the manner in which those rents are dissipated in the first place—i.e. by excessive use of intensive inputs or by excessive entry of capital.

7. Conclusion

This paper utilizes the Bering Sea RKC fishery as a case study to make several contributions toward an enhanced understanding of the process and sources of rent generation with the introduction of ITQs. First, we draw attention to the multiple margins across

[31]Rents for the LE_{232} fishery are 85% of the maximum possible rents with 232 vessels when evaluated at the largest examined fuel price ($\rho^f = 10$).

[32]We are implicitly assuming here that fuel prices have no effect on the number of vessels that exist after ITQ introduction.

which rents are generated when property rights change in a fishery, distinguishing between extensive and intensive margins. Second, we use an unusually rich pre- and post-ITQ data set to uncover changes in deep structural choices in a fishery production setting. Third, we develop a unique conceptual micro-model of the fishing process that is sufficiently structural so as to be invariant to changes in management institutions. Our conceptual model of choices about the deployment of gear over space and time is framed in terms of a production function, yet it is not the sort of production function typical in most fisheries analyses. Rather than expressing output as a direct function of inputs such as fuel, labor time, or bait, we view these conventional inputs as derived outcomes of deeper structural decisions involving the deployment of gear in space and time. Finally, we calibrate the model using data from the crab fishery and embed the micro model into a sector-level model. This allows us to experimentally "unbundle" the ITQ treatment, decomposing its impacts into intensive and extensive margin changes associated with consolidation and the allocation of individual property rights. We use this decomposition to explore the subtle and nuanced ways in which changes in fishing behaviors, costs and rents are influenced by the joint interplay of incentives on intensive and extensive margins.

The application in this paper is to a somewhat unconventional industry with its own peculiar and specialized production process. However, the problem we are tackling—namely specifying the relevant margins across which real-world production processes are adjusted in response to a policy change—is a general one. Much economic analysis over-simplifies production processes by collapsing context-specific micro-margins into aggregated and general production and cost functions that are themselves depicted as functions of aggregated inputs or input indices.[33] In his famous critique, Lucas [24] summarizes the implications of lumping policy-relevant behavioral margins into aggregated models of behavior. In particular, Lucas points out that if neglected behavioral margins are impacted by a policy change, then there is no reason to expect that oversimplified aggregate relationships will be stable to interventions in management. In general, accurate assessment of the impacts of a policy intervention requires a description of the production process that is sufficiently "deep" so as to be invariant to changes in management institutions.

[33] A notable exception to this is Bresnahan and Ramey's [38] work on production adjustment in the U.S. automobile industry, which careful accounts for the multiple margins of production variation and the resulting nonconvexities in a firm?s cost structure.

We make use of abstractions to simplify a complex situation, and some of our abstractions simplify important mechanisms that might be addressed in additional research. Our empirical results display the obvious heterogeneity that exists in the fishery, which we ignore in order to simplify the computation and interpretation of our results. In reality, heterogeneity plays an additional role in the consolidation process, as indicated by the gravitation of production to larger vessels in Figure 2a. Thus, the rents we identify as consolidation-induced rents do not take into account rents generated by the gravitation of quota to more efficient vessels. The ITQ- induced rents in our model therefore serve as a lower bound for rents generated from introducing ITQs to a heterogeneous fleet. In addition, while our model incorporates the concepts of timing and spacing in the harvesting production process, we essentially treat the fishing process as static. We would expect, however, that over the course of the season, harvesters obtain information in regards to the spatial whereabouts of the fish stock and change their input usage accordingly [39]. Thus, further research is needed to isolate harvesting behavior that may be better described as searching for crab than as fishing.

Our results provide a detailed and nuanced accounting of the many margins of fishing behavior influenced by ITQs, and the consequent sources of rent generation from the implementation of secure rights. Importantly, we show that the total effect of ITQ introduction is the sum of two competing effects. In particular, ITQ incentives tend to slow down the intensity of harvesting over time and space as harvesters slow down their speed of travel, lift fewer pots per day, employ fewer pots, and increase the distance between pots. Consolidation, in contrast, tends to act in the opposite direction, intensifying harvesting behavior over time and space, as fewer boats increase input use to harvest their increased allocations. Therefore, in contrast to the received wisdom, it is not necessarily the case that ITQ introduction results in less "intensive" behavior. Details—such as the initial magnitude of excess capital and congestion in the fishery, and the extent to which a fishery consolidates—matter.

Rent generation and reductions in average variable cost occur from both the incentives reflected in the security of harvesting rights and reducing the size of the fleet. Our results suggest that—for the RKC fishery—the majority of rent generation from ITQ introduction stems from the elimination of excess capital and its associated seasonal opportunity cost, in addition to increases in the average scale of operation. This is despite the fact that ITQ incentives generate a substantial reduction in average variable costs. The role played by consolidation reflects the fact that the RKC fishery is capital intensive; large multi-million dollar investments and associated high fixed costs are necessary to successfully access crab in the harsh environment of the Bering Sea. Perhaps more importantly, the relative contribution of consolidation reflects the fact that there were restrictions on the technological capacity of the fleet to dissipate rents along the intensive margins due to limits on traveling velocity. Different findings on the relative contributions of consolidation versus incentives may emerge from fisheries that are less capital intensive—including nearshore fisheries such as sea urchin, salmon, or sablefish. Incentive effects may also dominate in settings in which a fairly stringent limited entry program exists before the introduction of ITQs—limiting post-ITQ consolidation. More generally, our analysis indicates that the magnitude and source of rent generation under ITQs critically depends on the manner and degree of rent dissipation before ITQs are implemented.

The RKC fishery provides an example of how substantial rent generation can occur through consolidation alone; however, it is important to point out that management programs that promote consolidation—such as vessel buyback programs—without harnessing the incentives reflected in secure harvesting rights may not be able to sustain the increased economic rents in the long run. For the RKC fishery, a binding maximum velocity limits the extent to which harvesters can compete away fishery rents. A positive shadow value of velocity indicates that incentives exist for limited entry harvesters to invest in faster boats in the longer run, and these incentives motivate boat builders to design boats that relax the technological constraint. While the velocity constraint is real in this fishery, it may be viewed more generally as a metaphor for any temporarily binding technological or regulatory constraint in very flexible fishing processes under limited entry. Without secure harvesting rights, incentives always exist to intensify input use to compensate for any binding constraint, and to adopt new technology and practices that relax the constraint. In an LE fishery without secure rights, we would thus expect further dissipation of the consolidation gains from intensifying the race to fish, as indicated in Figure 6, in addition to dissipation from misdirected rent seeking investments in technology and methods to gain an ultimately ephemeral advantage over one's competitors. This general lesson has been well known since the early literature on capital stuffing and from the considerable practical experience with limited entry fisheries.

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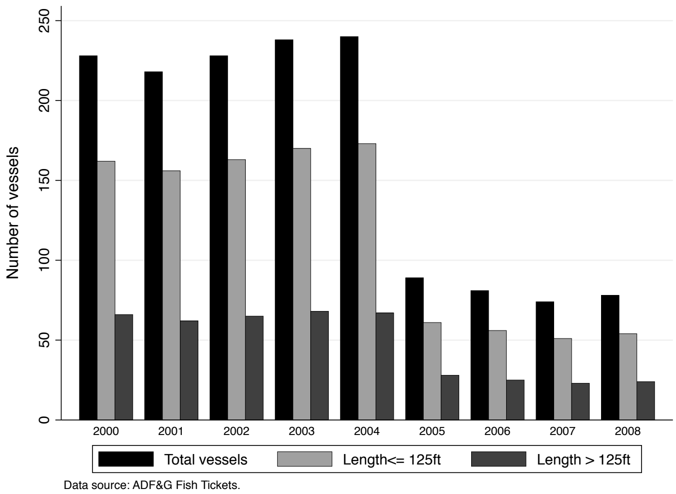

Figure 1: Number of vessels by year and vessel class.

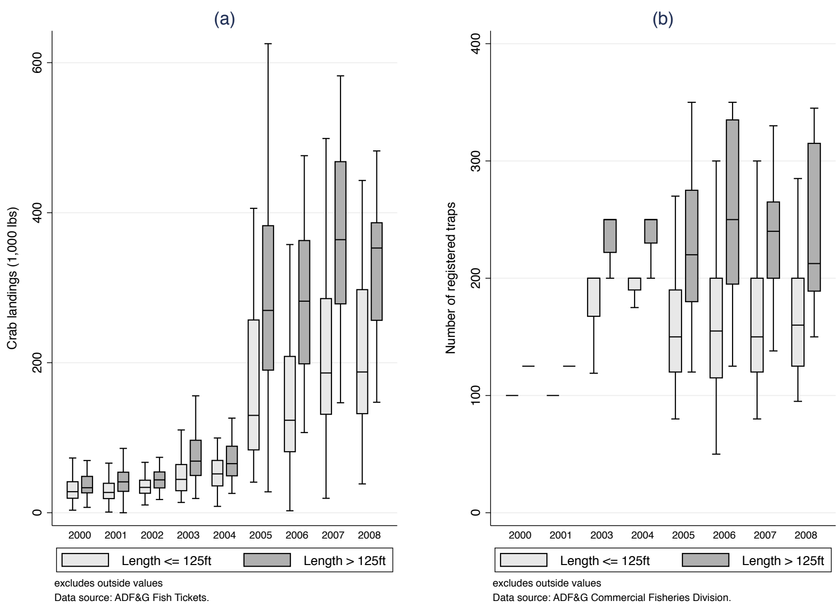

Figure 2: Box-and-whisker plots of (a) seasonal crab harvests and (b) registered traps (pots), by season and vessel class. Outliers excluded for confidentiality. Data on registered pots in 2002 was not available.

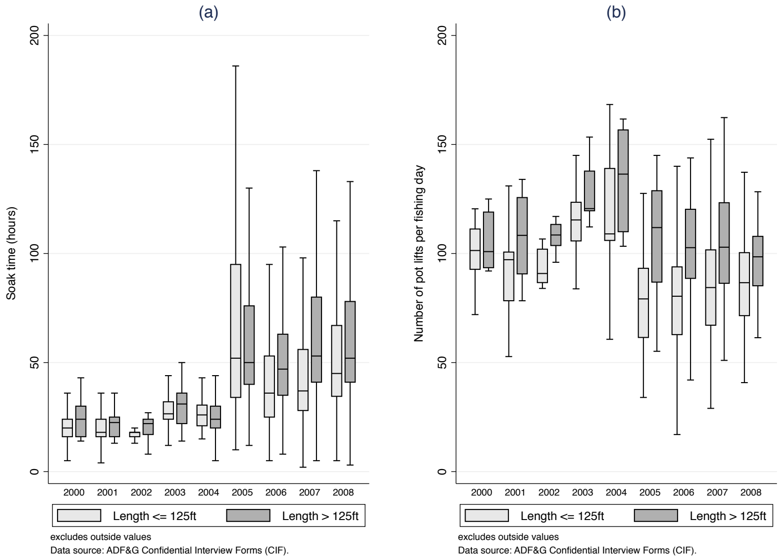

Figure 3: Box-and-whisker plots of (a) soak time (hours) and (b) pot lifts per fishing day, by season. Outliers excluded for confidentiality.

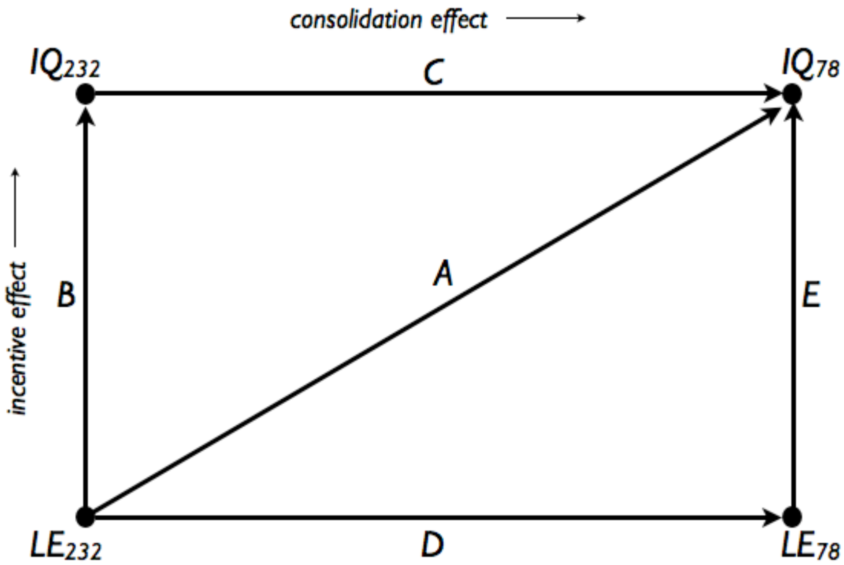

Figure 4: Depiction of the experimental design for separating the effects of ITQ introduction into consolidation effects and incentive effects. Treatment A captures the total effects, treatments C and D capture the consolidation effects, and treatments B and E capture the incentive effects. Note that this is only a depiction of the multiple treatments conducted in our hypothetical experiment so that the distance between any two points has no quantitative significance.

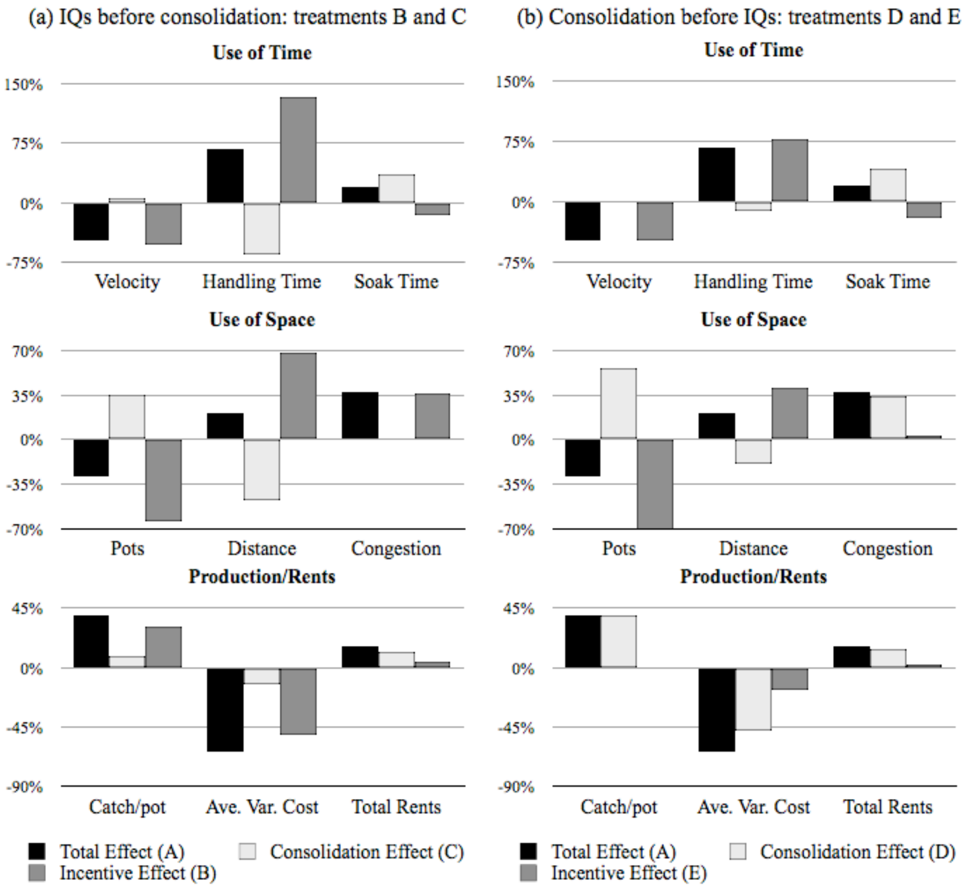

Figure 5: Decomposing the total percentage effects from introducing ITQs. The total effect of ITQs (treatment A) is the percentage difference between IQ_{78} and LE_{232}. Figure (a) depicts the composition of the total effects that arises from introducing IQs before consolidation while Figure (b) depicts the composition of the total effects by allowing consolidation before introducing IQs. Note that for both Figure (a) and (b), the sum of the incentive effects and the composition effects are equal to the total effects.

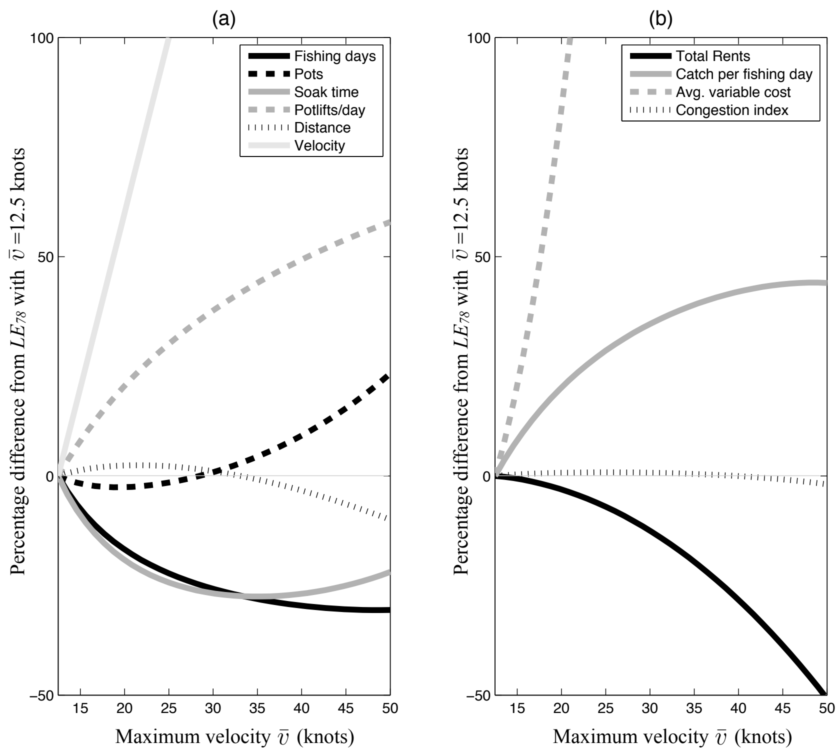

Figure 6: Race to fish and rent dissipation in a limited entry fishery—Simulated outcomes in the LE_{78} fishery as the maximum velocity ($\bar{v}$) constraint is relaxed from $\bar{v} = 12.5$ knots. Simulated outcomes are measured as the percentage difference from a LE_{78} fishery with $\bar{v}$=12.5 knots.

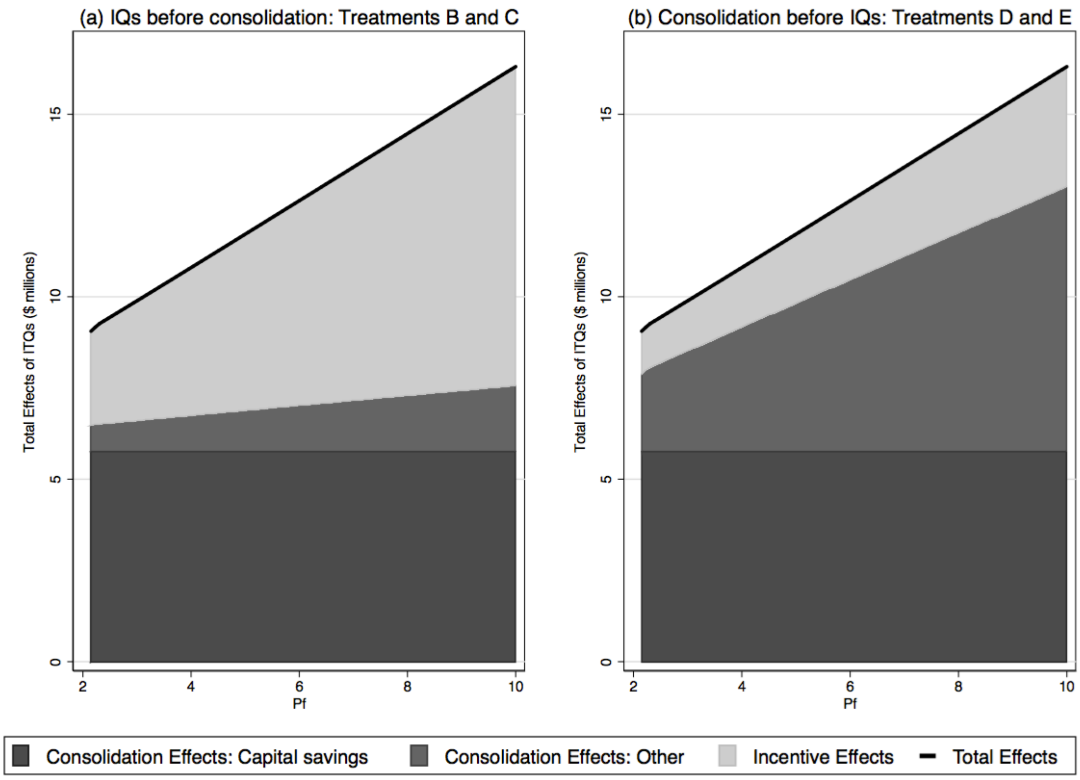

Figure 7: Total effects of ITQs with rising fuel prices—decomposed into incentive effects and consolidation effects. Consolidation effects are further separated into rents generated by eliminating excessive vessel rental costs (capital savings) r and all other remaining rents from consolidation (other).

Calibration Point	Actual Median (1) 2004	Actual Median (2) 2006	Actual Median (3) Difference (%)	Model Prediction (4) 2004	Model Prediction (5) 2006	Model Prediction (6) Difference (%)
Soak time (days)	1.02	1.54	+50.94	1.24	1.59	+28.23
Pot lifts/day	111.67	83.17	-25.52	143.58	80.03	-44.26
Fishing days/trip	3.00	4.50	+50.00	3.71	5.46	+49.87
Registered pots	200.00	150.00	-25.00	178.62	127.38	-28.69
Crabs/pot	21.00	30.00	+42.86	27.06	38.14	+40.95

Table 1: Calibration and model validation—actual medians and model predictions for 2004 and 2006. The actual medians for 2004 were used as calibration points.

	Use of Time				
Institution	Velocity (knots)	Pot Lifts per Fishing Day	Soak Time (days)	Fishing Days	Trips
(a) LE_{232}	12.5	143.6	1.24	3.71	1
(b) LE_{78}	12.5	160.1	1.74	6.45	1
(c) IQ_{232}	5.94	61.4	1.05	5.43	1
(d) IQ_{78}	6.55	85.2	1.49	10.29	2
	Use of Space				
Institution	Pots	Distance (nm)	Inverse Cong. Index	Own Inverse Cong. Index	
(a) LE_{232}	178.61	1.10	0.716	0.974	
(b) LE_{78}	278.88	0.89	0.961	0.977	
(c) IQ_{232}	64.67	1.85	0.975	0.981	
(d) IQ_{78}	126.65	1.33	0.979	0.982	
	Production/Rents				
Institution	Catch per Day (crabs)	Ave. Variable Cost ($/crab)	Rents per Vessel ($)	Total Rents ($)	
(a) LE_{232}	2581	2.24	234,370	54,373,840	
(b) LE_{78}	4412	1.18	795,850	62,076,300	
(c) IQ_{232}	1762	1.10	244,590	56,744,880	
(d) IQ_{78}	2765	0.81	810,220	63,197,160	

Table 2: Simulation results for different institution types and number of vessels. The total effect of ITQ introduction is row (a) vs. row (d) (treatment A). The incentive effect is row (a) vs. row (c) (treatment B) or row (b) vs. row (d) (treatment C). The consolidation effect is row (a) vs. row (b) (treatment D) or row (c) vs. row (d) (treatment E). Note that the rents reported here are measured before the payments to labor, reflecting the nature of the share system in the RKC fishery.