Unraveling the Multiple Margins of Rent Generation from Individual Transferable Quotas

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Abstract

The prediction that individual transferable quotas (ITQs) induce changes along the extensive margin via consolidation of quota among fewer vessels has been extensively documented. In contrast, behavioral changes along the intensive margin in response to ITQ incentives have been relatively neglected. We use the 2005 introduction of ITQs to the Bering Sea red king crab fishery to decompose the sources of rent generation across both margins. We develop a conceptual model of the harvesting production process that captures the principal decisions made by the skipper and crew throughout a fishing season. We depict the decision-making environment under pre- and post-ITQ settings by modeling limited entry and ITQ fisheries as two different symmetric games. We show that the effects of introducing ITQs are potentially multi-faceted, non-monotonic, and at times contrary to prior expectations. For the crab fishery we find that the bulk of rents were generated across the extensive margin.
1 Introduction

Economists have advocated rights-based management regimes for over 40 years as a means to addressing the failure of command and control regulatory institutions. In general, rights-based institutions create a significantly different incentive system for fishermen. Rather than racing for a larger share of the harvestable stock, fishermen are motivated to increase the present value of their access-rights, leading to changes in fishing practices, consolidation, cost saving, and resource productivity investment (Wilen, 2006). Formal studies and the accumulation of experience from a number of individual transferable quota (ITQ) managed fisheries have yielded a fairly mature and nuanced understanding of the potential impacts of ITQs (Abbott et al., 2010, Casey et al., 1995, Dewees, 1989, 1998, Dupont and Grafton, 2001, Grafton et al., 2000).

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 vessels (Grafton, 1996). 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 that pre-ITQ vessels are typically operating under increasing returns to scale (Lian et al., 2010). 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.”

We would expect that ITQs also 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. 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 (Wilen, 1979). Yet this aspect of the rent generating process under ITQs has been relatively neglected in the literature. ITQs generate discrete changes in the motives of harvesters, away from

\[1\text{Subsequent work has examined the importance to rent dissipation of the elasticity of substitution between regulated and unregulated inputs in two-input models under atomistic behavior (Campbell, 1991, Campbell and Lindner, 1990, Deacon et al., 2011). More recent work generalizes to multiple restricted and unrestricted inputs under first-best and open access settings (Abbott and Wilen, 2009).} \]
“racing” for a larger share of the TAC and toward quota value maximizing behavior. 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 affect variable input use, costs, and rents?

The precise nature of anticipated changes along the intensive margin has not been clearly articulated in the conceptual literature, nor has it been rigorously examined empirically. Moreover, there is reason to expect that the two sources of rent generation are likely to be muddled empirically because actions taken along the two margins may counteract 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.

In this paper, we address the incomplete narrative of rent generation from ITQ introduction by constructing a model of the fishing production process that allows us to differentiate between rents generated along both the extensive and intensive margins. It is important to understand that conventional models of the fishing production process are not rich enough to decompose changes induced by ITQs across multiple margins of behavior. The production process of fishing is unique (compared, for example, to agriculture) because the firm must accommodate its activities to the spatiotemporal dynamics of a fugitive resource. The production process of capture fisheries thus involves the strategic use of time and space as primary decision variables. Therefore, many traditional “inputs” such as rates of fuel usage, labor time, bait, and gear are not direct choice variables; rather, they are indirect outcomes of deep structural decisions over the temporal and spatial deployment of harvesting gear. If the combination of these micro-level decisions is shaped by the incentives inherent in management institutions, then there is no reason to expect that conventional models of the fishing production process will be stable to interventions in management. Conventional models of fishing production are
thus limited in their use for predicting the outcomes of ITQ introduction because they incorrectly assume that the relationship between derived inputs (i.e. labor and fuel) and final outputs is the same before and after the introduction of ITQs. Accurate assessment of the impacts of ITQs therefore requires a description of the production process that is sufficiently structural so as to be invariant (at least in the short run) to changes in management institutions.

We use the 2005 introduction of ITQs to the Bering Sea red king crab (RKC) fishery as a platform to describe the nature of a representative harvester’s fundamental production process and the extent to which structural decision variables are influenced by ITQs.\textsuperscript{2} We take advantage of a rich and detailed pre- and post-ITQ survey data set 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.\textsuperscript{3} We use these data to develop and parameterize a novel conceptual model of the crab harvesting production process that captures the main decisions made by the skipper and crew throughout a fishing season with respect to traveling to and from fishing grounds and the process of setting and lifting traps (or pots). We capture the decision-making environment under pre- and post-ITQ settings by modeling a limited entry and an ITQ fishery as two different symmetric games played between all participating harvesters in the fishery, with each game differing according to the regulatory setting of the fishery. We then utilize a sector-level simulation model to generate policy “experiments.” By using my model to simulate controlled counterfactual scenarios, we are able to unravel the multiple treatments embodied in the switch to ITQ management, thereby distinguishing between behavioral drivers of changes along the extensive margin, where quota is consolidated across fewer vessels, versus drivers associated with fundamental incentive changes under ITQs. 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.

\textsuperscript{2}Previous endeavors to model the production process of trap-based fisheries include Briand et al. (2004) (the Bristol Bay RKC fishery) and Holland (2011) (the Maine lobster fishery).

\textsuperscript{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. An appendix containing a detailed description of each dataset is available upon request.
of secure harvesting rights.

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.

The immediate result of ITQ introduction was a reduction in the fleet size to approximately one-third of its pre-derby size (Figure 1), a threefold increase in the typical number of fishing days per season (Abbott et al., 2010), 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. 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 intro-

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4Data on the number of pots registered for a given season comes from the ADF&G Commercial Fisheries Division.
Figure 1: Fleet size - Number of vessels by year and vessel class.

Figure 2: Consolidation and trap use - 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.
duction 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 4). 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.5

While the change in the intensive use of inputs is stark, there are confounding factors unrelated to ITQ introduction, such as weather conditions and output prices, that could be important in explaining the changes we see in Figure 3. To control for these factors, we estimate a median regression of the log of soak time and pot lifts per fishing day on average temperature and wind speed, ex-vessel prices, and vessel length, including fixed effects for different sizes of pots and for different seasons.6 Using the estimated seasonal fixed effects, we compute the predicted percentage difference in median pot lifts per fishing day and soak time relative to 2004, along with their corresponding cluster robust 95% confidence intervals (Figure 4).7 The results support the general findings from the box-and-whisker plots in Figure 3 while the upward trend in soak time prior to rationalization could be from the increase in pot limits in 2003 and 2004.

Although the increase in soak time and decrease in pot lifts per fishing day after ra-

5See NOAA (2010) for a comprehensive review of all rationalized Alaskan crab fisheries five years after ITQs were implemented.

6An attempt was made to control for fuel price, pot limits, and TAC, but they were ultimately dropped due to multi-collinearity problems. The trend in all three variables is to increase over seasons with little to no variability within a season, leaving very little independent variation (with the inclusion of seasonal fixed effects) to identify their effect on input usage.

7Cluster robust confidence intervals were obtained from 500 pair-wise bootstraps, where clusters are defined at the trip level.
Figure 3: Soak time per pot and pot lifts per day - Box-and-whisker plots of (a) soak time (hours) and (b) pot lifts per fishing day, by season. Outliers excluded for confidentiality.
Figure 4: Median regression for soak time per pot and pot lifts per day - Predicted percentage change in (a) median soak time and (b) median pot lifts per fishing day, relative to 2004. The dashed vertical line indicates the season immediately prior to ITQ introduction (2004) while the dotted vertical line indicates the season immediately prior to the relaxation of pot limits to twice their previous size.
tionalization are clear, their causes are less evident. Are the changes due to the allocation of a guaranteed portion of the TAC under the ITQ program, or are they due to the consolidation of the annual TAC upon fewer vessels? While the elimination of redundant capital was an intended consequence of rationalization, it may confound changes in fishing practices due to the incentives generated under ITQs with the elimination of excess capital that can occur under non-rights-based limited entry programs. 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? In order to understand why we observe such changes in fishing practices, it is necessary to move beyond the descriptive analysis presented above to a structural model capable of depicting harvester behavior under different 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 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. 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.

9Our 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.
time associated with various decisions. A season generally involves multiple trips, each of which consists of multiple days of more or less continuous pot lift activity. The model captures the main decisions made by the skipper and crew 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:

\[ S = \text{soak time for a single pot (days)} \]
\[ N = \text{number of pots in a string (pots/string)} \]
\[ d = \text{distance between pots (nm)} \]
\[ v = \text{velocity of travel between pots (nm/day)} \]
\[ \tau^h = \text{pot handling time (days/pot)} \]
\[ T^f = \text{fishing days in a trip (days/trip)} \]
\[ t = \text{number of trips during the season} \]
\[ P_L = \text{total pots lifted during the season (pots/season)} \]

We assume that skippers distribute a string of uniformly spaced pots around their chosen fishing grounds in a “working circle”. Each vessel is assumed to use one string per trip, but the 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. We define pot handling time \( \tau^h \) as the time spent retrieving, baiting, and setting a pot \( \tau^s \) plus the time spent traveling to the next pot. Assuming for simplicity that \( \tau^s \) is exogenous, we have the following relationship for pot handling time:

\[ \tau^h = \tau^s + \frac{d}{v}. \]  

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. The optimal size string is such that, by the time the vessel has worked its way around the entire string, retrieving, baiting and resetting each pot, the first pot is ready to pull to

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10 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.
start the process over again. This implies that soak time must be equal to the number of pots per string times the handling time per pot,

\[ S = \tau^h N, \]  

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 \( T \):

\[ (T^t + T^f)t = T, \]  

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.\(^{11}\) We assume that pots are lifted/set continuously throughout all fishing days for a trip until the end of the season. Furthermore, we 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

\(^{11}\)We differentiate between pots set and pots lifted 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.
travels between shore and the fishing grounds. Thus, we have the following relationships:

\[ \tau^h P^S = T^f t \]
\[ P^L = P^S - N, \]

where we have ignored any pot lifts that occur after the season is ended. This 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 identities 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 \( \tau^h \), pots lifted per season \( P^L \), pots set per season \( P^S \), and time spent fishing during a trip \( T^f \):

\[ S(d, v, N) = N \left( \tau^s + \frac{d}{v} \right) \]
\[ \tau^h(d, v) = \tau^s + \frac{d}{v} \]
\[ T^f(t, T) = \frac{T}{t} - T^s \]
\[ P^S(d, v, t, T) = \frac{T^f(t, T)}{\tau^h(d, v)} t \]
\[ P^L(d, v, N, t, T) = P^S(d, v, t, T) - N \]

The identities 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-Bertalanffy type equation (Briand et al., 2004, Briand and Matulich, 2001),

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

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 \( \gamma \) represents the rate at which the asymptotic catch is reached (Figure 5). 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,

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

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 \( \lambda^d \) and \( \lambda^N \) 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 (Figure 6a) 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 (agglomeration effect) but each pot will catch a
smaller fraction of the attracted crab population (congestion effect). 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 sigmoid-shape of the cross-pot congestion index curve (Figure 6b) can be interpreted as a congestion or stock externality across vessels. 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.

Figure 5: Production function for a single pot - Per pot Production: \( f(S) = D \left(1 - e^{-\gamma S}\right) \), with \( \delta = 1 \) (i.e. no congestion).
Figure 6: Inverse congestion index function - (a) Own-pot congestion and (b) cross-pot congestion.

We can write a representative vessel’s seasonal production function as

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

Thus, the amount of crab caught in a season depends on a complex relationship between the distance traveled around a string, 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 caught 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 be a decreasing function of time spent fishing and traveling to shore during a trip, so that the effective price of crab \( \rho \) is

\[
\rho(t, T) = \tilde{\rho} \left( 1 - \theta \left[ T^f(t, T) + \frac{1}{2}T^a \right] \right), \tag{10}
\]
where $\sigma > 1$ and $\theta > 0$, guaranteeing that $\rho(\cdot)$ is concave, and $\bar{\rho}$ is the ex-vessel price of crab.

At this point, it is worth discussing how the seasonal production function $F(\cdot)$ in equation (9) is different from many conventional production functions. First, $F(\cdot)$ does not necessarily satisfy the convenient property of monotonicity, as can be seen in the following “marginal products” of distance, velocity, and number of pots:

$$
F_d = \frac{P_d^L(\cdot)\delta_d(\cdot)f_d(\cdot)}{\sigma_d(\cdot)} + \frac{P_d^L(\cdot)\delta_d(\cdot)f_d(\cdot)\sigma_d(\cdot)}{\sigma_d(\cdot)} + \frac{P_d^L(\cdot)\delta_d(\cdot)f_d(\cdot)\sigma_d(\cdot)}{\sigma_d(\cdot)}
$$

Further, the potential negativity of the marginal product does not arise from diminishing marginal returns per se, but because each input affects production along multiple dimensions, some of which are competing. For example, enlarging the distance between pots or increasing the number of pots in a string, *ceteris paribus*, has a positive effect on catch per season by decreasing pot congestion and by elongating the soak time of each pot in the string, but has a negative effect on catch per season by reducing the number of pots lifted over the course of a season. In opposite fashion, increasing the velocity of travel between pots has a positive effect on catch per season by increasing the number of pots lifted during the season but reduces catch per pot by reducing the soak time of each pot in the string.

Second, the harvesting production technology summarized by $F(\cdot)$ is not convex so that first-order conditions for the profit maximization problem (described in Section 4) are not sufficient for the determination of a best response function. While this does not overly complicate our numerical methods that follow, it provides another example

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12 An exposition on the typical properties of conventional production models is covered in Section ??.

13 For the sake of simplicity, the marginal products assume a fixed season length $T$. Including an endogenous season length, the nature of which is presented in Section 4, complicates the description of the marginal products but does not change the general conclusions of the discussion.
of how a production function that incorporates the subtle interdependencies that exist in a spatiotemporal production process does not necessarily satisfy many convenient properties that assist in characterizing analytical solutions to behavioral models.

3.2 Seasonal costs

With the production function defined above, we now focus on the variable costs per season, which we define to be

$$C(d, v, N, t, T) = c^u + c^o + c^t,$$  \hspace{1cm} (12)

where cost per season is divided into three components:\footnote{Our method of breaking apart costs in such a way as to capture the true primal relationships between production inputs is similar to the decomposition of vessel expenditures in Abbott and Wilen (2009).} 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 pots, and the cost of labor provisions; and travel costs $c^t$, 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 multiplied by the number of pots pulled throughout the season, and daily labor costs $c^\ell$ times the length of the season $T$. That is,

$$c^o = P^S(d, v, t, T) \left( \frac{\text{set cost}}{\text{pot}} + \frac{\text{steam cost}}{\text{pot}} \right) + c^\ell T$$

$$= P^S(d, v, t, T) (c^p + \phi(d, v)) + c^\ell T. \hspace{1cm} (13)$$

Importantly, crew labor in the RKC fishery typically receives a share of revenues after certain costs have been deducted (Abbott et al., 2010) so that $c^\ell$ is interpreted as daily labor provisions, such as food, rather than as daily crew remuneration.\footnote{In general, not accounting for the lay system can result in a poor representation of commercial fishing behavior (McConnell and Price, 2006). Indeed, the interpretation of $c^\ell$ as daily labor provisions...}
To capture the technological realities of traveling between pots, we model steaming cost per pot \( \phi(\cdot) \) in a way that represents fuel consumption as a function of velocity and distance:

\[
\phi(d, v) = \alpha v^\beta d,
\]

so that steaming cost 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, RS assume vessels can only travel up to a maximum velocity of \( \bar{v} \). Importantly, \( \alpha, \beta, \) 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 as a function of \( d, N, v, \) and \( t \):

\[
C(d, v, N, t, T) = c^N N + P^S(d, v, t, T) \left( c^p + \alpha v^\beta d \right) + c^T T + c^t t + r
\]

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 Behavioral model

Each fishery, limited entry (LE) and ITQ, is represented by a static game of complete information with an endogenous season length \( T(\cdot) \) that is determined by the actions of all players. Our model can alternatively be interpreted as a dynamic game with commitment at the beginning of the season 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. Harvester's is important for calibrating our model to mimic the actual behavior we see in the RKC fishery.
are assumed to be homogenous and the number of harvesters \( \eta \) in each fishery is assumed to be 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 \( t \in \{1, 2, 3, \ldots \} \) they will make during the season. Players are assumed to choose actions to maximize a payoff function \( \Pi \) – 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 \( H \):

\[
\max_{d,v,N,t} \quad \Pi = \rho(t, T(\cdot))P^L(d, v, N, t, T(\cdot))g(d, v, N, N_{-t}) - C(d, v, N, t, T(\cdot))
\]

subject to \( \frac{F(d, v, n, t, T(\cdot), N_{-t})}{t} \leq H. \) \( (16) \)

Note that the objective function in (16) is not weighted by the maximizer’s share of seasonal profits. Since the costs we account for in equation (15) are typically deducted from revenues prior to calculating shares, the objective function for the decision maker is nothing more than a monotonic transformation of (16). This convenience allows us to be ambiguous about whether the objective function in (16) 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 two games differ only in assumptions about the determination of season length. We assume that season lengths are determined such that a biologically determined TAC is not exceeded. If the fishery is regulated by ITQs, then season length is simply modeled as the length of time it takes for a vessel 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 ITQ fishery has the following endogenously determined season length \( T^{ITQ} \):

\[
Q = F(d, v, N, t, T^{ITQ})
\]

\[
\Rightarrow T^{ITQ} = \left[ \frac{Q}{g(d, v, N, N_{-t})} \right] + N \ t^h(d, v) + T^t t. \] \( (17) \)
Each identical harvester is assumed to be allocated the same portion of the TAC so that there are no gains to trade remaining in the quota market, resulting in $Q = \frac{TAC}{\eta}$ (Costello and Deacon, 2007, Fell, 2009). Note that even though harvesters are 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.

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

$$TAC = F(d, v, N, t, T^{LE}) + (\eta - 1)F(d_{-i}, v_{-i}, N_{-i}, t_{-i}, T^{LE})$$

$$\Rightarrow T^{LE} = \frac{TAC + \left(\frac{r_i}{\gamma_i} t + N\right) g(\cdot) + (\eta - 1) \left(\frac{r_i}{\gamma_{i-1}} t_{-i} + N_{-i}\right) g_{-i}}{\frac{g(\cdot)}{\gamma} + (\eta - 1) \frac{g_{-i}}{\gamma_{-i}}},$$

where we use the definition of $F(\cdot)$ in equation (9) and substitute in the various identities in (6) to obtain equation (18). 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.

Given the normal-form representation of the two games above, it is important to note that each game is symmetric: 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. While choosing to represent each fishery as a symmetric game limits our ability to explain the heterogeneity that exists in the RKC fishery, it greatly simplifies our analysis by allowing us to focus on symmetric pure-strategy Nash equilibria (SNE) as outcomes for our behavioral model. While the lack
of quasiconcavity of the payoff functions and the non-convexity of the strategy set does not guarantee the existence of a SNE for all possible combinations of model parameters, 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 I consider.

5 Discussion

5.1 Solution methods and model verification

Given the complicated nature of the harvesting production process, an analytical solution to the maximization problem in (16) cannot be derived for either the LE or ITQ fishery. 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 (16) is a mixed integer nonlinear programming problem that is solved in MATLAB. 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. An appendix containing details about the calibration process, the data used for calibration, our numerical methods, and the parameter values used in our simulations is available upon request.\(^{16}\)

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.\(^{17}\) 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

\(^{16}\)MATLAB code is also available from the author upon request.

\(^{17}\)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.
Despite the complex nature of the harvesting process, our simple calibrated model does fairly well at predicting both the median fishery outcomes and the relative behavioral changes witnessed in the data.

<table>
<thead>
<tr>
<th>Calibration Point</th>
<th>Actual Median</th>
<th>Model Prediction</th>
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<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>Soak time (days)</td>
<td>1.02</td>
<td>1.54</td>
</tr>
<tr>
<td>Pot lifts/day</td>
<td>111.67</td>
<td>83.17</td>
</tr>
<tr>
<td>Fishing days/trip</td>
<td>3.00</td>
<td>4.50</td>
</tr>
<tr>
<td>Registered pots</td>
<td>200.00</td>
<td>150.00</td>
</tr>
<tr>
<td>Crabs/pot</td>
<td>21.00</td>
<td>30.00</td>
</tr>
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</table>

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.

5.2 Hypothetical experimental design

While we are concerned with understanding the overall effects of ITQs on the production margins and rents of crab harvesters, we would also like to decompose the total effects of ITQ introduction into changes in fishing practices due to the elimination of vessels from the fishery (consolidation effects) and those that arise due to introducing secure harvesting rights (incentive effects). Doing so allows us to investigate the effectiveness of other fishery regulatory institutions that either eliminate excess capital without changing harvesting incentives, such as vessel buyback programs, or allocate harvesting shares to the TAC but prohibit quota trading between harvesters.

In order to examine these alternative regulatory scenarios, we use a series of model simulations to assess multiple institutional “treatments” within a hypothetical experiment (Figure 7) that separates the total effects of ITQs on a representative vessel into consolidation effects and incentive effects. LE$_{232}$ in Figure 7 denotes an LE fishery with 232 vessels, representing the RKC fishery prior to ITQ introduction, and serves as the baseline in our hypothetical experiment. The total effects of introducing ITQs (ITQ$_{78}$ -

---

18Ex-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.
are captured by Treatment A, which applies ITQs to \( LE_{232} \) and permits reduction of the fleet from 232 to 78 vessels.\(^{19}\)

Figure 7: Experimental design - 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.

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 7. The first set of treatments applies ITQs to \( LE_{232} \) but prohibits quota transfers so there is no exit from the fishery (treatment B), followed by a relaxation of trade prohibitions so that the ITQ fishery consolidates 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 application of ITQs

\(^{19}\)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 because factors that we were not able to control for in our median regression analysis due to multicollinearity problems, such as TAC and estimated crab abundance, were relatively similar in these two years. Thus, the percentage differences between \( ITQ_{78} \) and \( LE_{232} \) outcomes are analogous to the percentage difference in estimated seasonal coefficients from our median regression analysis in Figure 4.

24
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 treatment effects are not additively separable, so that sequencing of the treatments matters for their effects. That is, the effects of treatments B and E are not necessarily equivalent so that incentive effects depend on the number of vessels in the fishery before ITQs are introduced. Similarly, the effects of consolidation treatments C and D are conditional on the regulatory institution of the fishery.

5.3 Results

The results from each of the model simulations used in our hypothetical experiment in Figure 7 are presented in Table 2, where the use of production inputs have been grouped according to their use of time or space. To frame the following discussion, we consider increases in both velocity and pot lifts per day as indicators of temporal input intensification, while an increase in the number of pots used and a reduction in the spacing between pots are considered indicators of spatial input intensification. Note that spatial and temporal intensity are intricately connected in that temporal intensity depends on input use over space. For example, decreasing the distance between pots \( d \) increases both spatial and temporal intensity by increasing the number of pot lifts per day.\(^{20}\)

The total effects of ITQ introduction (Figure 8) 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 velocity 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, substantial rents are generated due to increases in daily productivity and reductions

\(^{20}\)To see this, note that pot lifts per day is the inverse of handling time \( \tau^h \) and that handling time decreases with a reduction in distance \( d \) between pots (equation 6).
<table>
<thead>
<tr>
<th>Institution</th>
<th>Velocity (knots)</th>
<th>Pot Lifts per Fishing Day</th>
<th>Soak Time (days)</th>
<th>Fishing Days</th>
<th>Trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) LE_{232}</td>
<td>12.5</td>
<td>143.6</td>
<td>1.24</td>
<td>3.71</td>
<td>1</td>
</tr>
<tr>
<td>(b) LE_{78}</td>
<td>12.5</td>
<td>160.1</td>
<td>1.74</td>
<td>6.45</td>
<td>1</td>
</tr>
<tr>
<td>(c) ITQ_{232}</td>
<td>5.94</td>
<td>61.4</td>
<td>1.05</td>
<td>5.43</td>
<td>1</td>
</tr>
<tr>
<td>(d) ITQ_{78}</td>
<td>6.55</td>
<td>85.2</td>
<td>1.49</td>
<td>10.29</td>
<td>2</td>
</tr>
</tbody>
</table>

### Use of Space

<table>
<thead>
<tr>
<th>Institution</th>
<th>Pots</th>
<th>Distance (nm)</th>
<th>Inverse Cong. Index</th>
<th>Own Inverse Cong. Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) LE_{232}</td>
<td>178.61</td>
<td>1.10</td>
<td>0.716</td>
<td>0.974</td>
</tr>
<tr>
<td>(b) LE_{78}</td>
<td>278.88</td>
<td>0.89</td>
<td>0.961</td>
<td>0.977</td>
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<tr>
<td>(c) ITQ_{232}</td>
<td>64.67</td>
<td>1.85</td>
<td>0.975</td>
<td>0.981</td>
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<tr>
<td>(d) ITQ_{78}</td>
<td>126.65</td>
<td>1.33</td>
<td>0.979</td>
<td>0.982</td>
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</table>

### Production/Rents

<table>
<thead>
<tr>
<th>Institution</th>
<th>Catch per Day (crabs)</th>
<th>Ave. Variable Cost ($/crab)</th>
<th>Rents per Vessel ($)^a</th>
<th>Total Rents ($)^a</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) LE_{232}</td>
<td>2581</td>
<td>2.24</td>
<td>234,370</td>
<td>54,373,840</td>
</tr>
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<td>(b) LE_{78}</td>
<td>4412</td>
<td>1.18</td>
<td>795,850</td>
<td>62,076,300</td>
</tr>
<tr>
<td>(c) ITQ_{232}</td>
<td>1762</td>
<td>1.10</td>
<td>244,590</td>
<td>56,744,880</td>
</tr>
<tr>
<td>(d) ITQ_{78}</td>
<td>2765</td>
<td>0.81</td>
<td>810,220</td>
<td>63,197,160</td>
</tr>
</tbody>
</table>

^aThe rents reported in this table are measured before payments to labor, reflecting the nature of the share system in the RKC fishery.

Table 2: Simulation results - Results for different institution types and number of vessels. The total effect of ITQ introduction is row (a) vs. row (d) (movement A). The incentive effect is row (a) vs. row (c) (movement B) or row (b) vs. row (d) (movement C). The consolidation effect is row (a) vs. row (b) (movement D) or row (c) vs. row (d) (movement E).

in average variable costs from increases in the scale of operation of remaining vessels as excessive capital is eliminated and as new incentives are introduced with secure harvesting rights.\(^{21}\)

Figure 8 also depicts the separation of the total effects of ITQ introduction into incentive and consolidation effects, where column (a) presents the effects from introducing ITQs before consolidation (treatments B and C) while column (b) presents the effects from effecting consolidation before introducing ITQs (treatments D and E). While the magnitudes of the consolidation and incentive effects differ between the two sets of treatments, their qualitative directions are consistent. Consolidation alone appears to have

\(^{21}\)We define average variable costs as the seasonal cost of production (15) minus the seasonal rental cost of a vessel \(r\), divided by the number of harvested crab within a season.
Figure 8: The effects of introducing ITQs - Decomposing the total percentage effects from introducing ITQs. The total effect of ITQs (treatment A) is the percentage difference between $ITQ_{T8}$ and $LE_{232}$. Figure (a) depicts the composition of the total effects that arises from introducing ITQs before consolidation while Figure (b) depicts the composition of the total effects by allowing consolidation before introducing ITQs. Note that for both Figure (a) and (b), the sum of the incentive effects and the composition effects are equal to the total effects.
the effect of intensifying harvester behavior in both the temporal and spatial dimensions as vessels increase scale of operations. In contrast, incentive effects in isolation seem to diminish the intensity of input use over time and space respectively. Thus, isolating the incentive and consolidation effects from ITQ introduction reveals that the total effects from ITQ introduction are the sum of two competing effects.

Perhaps counter intuitively, soak time per pot actually tends to decrease from incentive effects (and vice versa for consolidation effects). The reason for this is that soak time is jointly determined by spatial and temporal input use so that the increase in soak time that occurs from slower velocity and increased distance between pots is overwhelmed by the substantial reduction in the use of pots with incentives alone. However, this incentive is buffered somewhat by the effects of consolidation under the ITQ to employ more pots, due to scale economies. This result provides an example for which the consolidation effect dominates the incentive effect and suggests that the longer soak times witnessed with ITQ introduction in the RKC fishery may actually be due to consolidation rather than from ITQ-specific incentives.

A glance at Table 2 reveals that both LE fisheries generate a considerable amount of rents, despite the lack of secure harvesting rights. In particular, Figure 8 indicates that consolidation in an LE fishery, perhaps by relaxing trade restrictions or through a vessel buyback program, is capable of generating large increases in rents. The reduction in average variable costs with consolidation in the LE (and ITQ) fishery indicates that vessels are able to exploit scale economies, contributing to overall rent generation.

The ability to generate substantial rents in an LE fishery is perhaps surprising, since lack of secure harvesting rights is typically associated with the dissipation of fishery rents (Homans and Wilen, 1997). As has been demonstrated by Campbell and Lindner (1990) and Deacon et al. (2011), however, the extent of rent dissipation can be mitigated 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 this case, the key restrictions are the limit on the number of vessels in the fishery and the technological 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 9 presents the SNE outcomes for the $LE_{78}$ fishery for different levels of $\bar{v}$, relative to the $LE_{78}$ fishery with $\bar{v} = 12.5$ knots. As the maximum velocity increases, the true “race for fish” intensifies in the LE fishery; harvesters are induced to travel faster ($\bar{v}$ is always binding), lift more pots per day, drive up their average variable costs, and dissipate fishery rents. In the RKC case, it is thus a technological constraint—i.e. an upper bound on velocity and imperfect substitutability between velocity, distance, and number of pots—rather than the regulatory institution itself that allows the LE fishery to generate substantial rents in this fishery.\(^\text{22}\)

Figure 9: Increasing maximum velocity and rent dissipation - Outcomes from the $LE_{78}$ fishery for different levels of maximum velocity ($\bar{v}$). The percentage difference in (a) model predictions and (b) performance measures, relative to the $LE_{78}$ fishery with $\bar{v}=12.5$ knots.

\(^\text{22}\)This result was highlighted in interviews with skippers as I 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).
The analysis above provides some general insights into the behavioral changes and sources of rent generation that occur from the consolidation and incentive effects from ITQ introduction. At the same time, considering only LE and ITQ fisheries with 232 and 78 vessels limits our ability to fully explain why harvesters intensify their fishing practices with the elimination of vessels from the fishery. It is also clear from Figure 8 that incentive effects depend on the number of vessels in the fishery; thus, it is worth investigating whether our tentative conclusion that ITQ incentives have the effect of reducing the intensity of input usage over time and space is robust to different fleet sizes.

To further examine the behavioral effects from consolidation, we consider treatments C and D from our hypothetical experiment to be continuous along the interval between 78 and 232 vessels (Figure 10). Many interesting changes in harvesting behavior occur as vessels are successively eliminated from either fishery. First, a discrete shift in fishing practices, average variable costs, and daily productivity in the ITQ fishery marks the number of vessels at which the fleet can make the transition to two trips. This transition is not witnessed in the LE fishery since, for the number of vessels considered here, intensive derby behavior closes the season before the binding hold capacity constraint is reached. LE harvesters thus fail to collectively make the transition to two trips at a larger number of vessels—like the ITQ harvesters do—even though they would be better off from reducing the amount of crab deterioration that occurs from longer trips. In addition, the trend in behavioral changes by LE harvesters is not affected when the transition to a second trip is made (not pictured), whereas ITQ harvesters display a large reduction in the intensity of their fishing practices after making the transition to two trips. This is due to the fact that harvesters from each respective fishery are racing against two different things: harvesters from the LE fishery are racing against each other so that transitioning to a second trip means nothing more than an additional lump sum cost, whereas harvesters from the ITQ 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.

Second, the elimination of vessels from the fishery does not necessarily have a monotonic effect on the incentives to intensify input use with consolidation. This is seen by
<table>
<thead>
<tr>
<th></th>
<th>232</th>
<th>200</th>
<th>150</th>
<th>100</th>
<th>78</th>
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<th>60</th>
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<tr>
<td>(a) LE fishery predictions</td>
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</table>

Figure 10: Consolidation in the limited entry fishery - Reducing the number of vessels in the limited entry (LE) fishery. Changes in (a) LE model predictions and (b) LE performance measures, relative to $LE_{232}$.  

a reduction in spatial and temporal intensity as vessels are initially eliminated from the LE fishery (Figure 10a), indicating that there is a competing mechanism—which I call a congestion effect—that operates alongside the consolidation effect as fleet size becomes smaller. As vessels exit the fishery, the number of pots in the fishery decreases, reducing cross-pot congestion and improving catch per unit effort for the remaining vessels. Improved catch per unit effort, ceteris paribus, allows fishermen to pursue a more relaxed pace of fishing since crab deterioration is no longer as much of a threat as before, resulting in reduced temporal and spatial fishing intensity.\textsuperscript{23} The initial domination of the congestion effect indicates initial overcapacity in the LE fishery, placing fishermen on a relatively steep portion of the cross-pot inverse congestion curve. Productivity improvements from reduced congestion are initially so large in the LE fishery that the season length declines even as fleet size shrinks and the number of pot lifts per day decreases. As downsizing continues, however, the marginal effect on cross-pot congestion shrinks in importance as the inverse congestion index approaches one. Consolidation of the TAC on fewer vessels now becomes the dominant driver of behavior. With an increased threat of product deterioration and substantial costs from dividing a single trip into two, consolidation pressures fishermen to increase their catch rate per day of fishing, as indicated by the increasing shadow value of velocity in Figure 10b.\textsuperscript{24}

The ITQ fishery reveals a subtly different picture in that the initial non-monotonic effects of consolidation of TAC on fishing intensity witnessed in the LE simulations fail to materialize (Figure 11). Instead, the consolidation scale effect dominates throughout the entire range of the experiment. Congestion improves minimally in the ITQ fishery with smaller $\eta$ because the index is already near one in the ITQ_{232} fishery due to much lower numbers of pots per vessel than under limited entry (Table 2). This demonstrates that it is the combination of both a large number of vessels and lack of property rights

\textsuperscript{23}Simulations in which vessels are successively eliminated from the fishery while the TAC is adjusted so that seasonal catch per vessel remains constant confirm the role of the congestion effect. These simulations mimic the qualitative reduction in intensity I've noted. However, once the fleet reaches a size in which cross-pot congestion is no longer elastic to further downsizing, eliminating vessels while keeping seasonal catch constant no longer affects harvester behavior.

\textsuperscript{24}The shadow value of velocity is defined here as an individual harvesters 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.
for crab that causes congestion in the fishery, not just the number of vessels itself.

Figure 11: Consolidation in the ITQ fishery - Reducing the number of vessels in the ITQ fishery. Changes in (a) ITQ model predictions and (b) ITQ performance measures, relative to $ITQ_{232}$. The vertical line at 158 vessels indicates the transition from a season of one trip to two.

Lastly, velocity of travel remains binding at $\bar{v}$ for all $\eta$ in the LE fishery, and in fact, harvesters would travel faster as the number of vessels in the fishery decreases as indicated by the positive shadow value of velocity in Figure 11b. The binding maximum velocity forces harvesters to substitute imperfectly towards other inputs in order to increase their temporal input usage as consolidation intensifies, and it is this imperfect substitution that prevents LE fishermen from competing away their rents.

To test the robustness of our preliminary conclusion that incentive effects reduce harvesting intensity over both space and time, Figure 12 presents the treatment effects of introducing ITQs to a LE fishery over the interval between 232 and 78 vessels, while prohibiting quota transfers (analogous to treatments B and E in Figure 7). Despite
the complications induced by the discreteness of trips, the general patterns that emerge from Figure 12 support our earlier conclusions about ITQ incentives, namely that ITQ incentives have the effect of reducing the intensity of input usage over both time and space, the extent to which depends on fleet size. In addition, soak time per pot tends to decrease from incentive effects, regardless of fleet size. Furthermore, improvements in fishery rents and average variable costs tend to be greatest when quotas to the TAC are introduced to LE fisheries with excessive congestion.

Figure 12: Incentive effects - ITQ fishery results relative to an LE fishery with the same number of vessels. Relative changes in (a) model predictions and (b) performance measures. The vertical line at 158 vessels indicates the transition from a season of one trip to two in the ITQ fishery.
6 Conclusion

This chapter 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 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 me 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.

Our dissection of the harvesting process into decisions involving time and space is fairly unconventional, yet our model produces intuitive and believable results. 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 important role in the consolidation process, as indicated by the gravitation of production to larger vessels in Figure 2a. 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 (Marcoul and Weninger, 2008). 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 less 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. Reducing fleet size may not always intensify harvesting behavior, however, as reducing fleet size also reduces congestion in the fishery, inducing harvesters to respond as they would to ITQ incentives. In this particular application, the incentive effects dominate over most behavioral margins so that overall intensity in the fishery is reduced. However, this may not always be the case with all decisions, as illustrated by the domination of consolidation effects for soak time. 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 relative 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. 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.

It is also important to point out that management programs that promote consolidation without harnessing the incentives reflected in secure harvesting rights may not be able to sustain the increased economic rents in the long run. In this particular case, a binding maximum velocity limits the extent to which harvesters can compete away fishery rents. The positive shadow value of velocity in Figure 10b 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 dissipation of the consolidation gains from intensifying the race to fish, as indicated in Figure 9, in addition to dissipation from misdirected rent seeking investments in technology and methods to gain an ultimately ephemeral advantage over ones 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.

References


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