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Geographic Distribution of Commercial Fishing Landings and Port Consolidation following ITQ Implementation

Cameron Speir and Min-Yang Lee

We evaluate whether changes in geographic distribution of landings coincided with implementation of individual transferable quotas (ITQs) in the limited-entry groundfish trawl fishery on the U.S. Pacific coast. We use a spatial Theil index, kernel density functions of port revenue share, and Shorrocks index of intradistributional mobility to measure changes in spatial distribution. We find evidence of increased spatial concentration; however, this appears consistent with preexisting trends and not related to ITQs. Further, we find a high degree of intradistributional mobility in the revenue share of ports that coincided with ITQ implementation.

Key words: fishing communities, distributional impacts, fisheries, individual transferable quotas, industry concentration, Theil index, Shorrocks index

Introduction

In fisheries managed using individual transferable quotas (ITQs), participants are allocated shares of the total catch and are allowed to transfer their share to other participants. ITQs are a way to solve the common property market failure described by Gordon (1954) and have become an increasingly common fisheries management tool in a number of settings (Brinson and Thunberg, 2016). ITQs have been found to mitigate the "race to fish" (Birkenbach, Kaczan, and Smith, 2017), increase profitability (Weninger, 1998; Grafton, Squires, and Fox, 2000; Reimer, Abbott, and Wilen, 2014; Mamula and Collier, 2015), improve fishermen's safety (Pfeiffer and Gratz, 2016), and improve ecological outcomes (Costello, Gaines, and Lynham, 2008; Branch, 2009; Chu, 2009; Essington, 2010; Essington et al., 2012). However, ITQ programs may also alter the distribution of benefits from the fishery among user groups (Guyader and Thébaud, 2001; Brandt, 2005; Brandt and McEvoy, 2006). Potential distributional impacts include consolidation of fishing access privileges and higher barriers to new entrants (McCay et al., 1995; Pálsson and Helgason, 1995), windfall gains to actors who are initially granted quota for free (Matulich, Mittelhammer, and Reberte, 1996; Copes et al., 2004), loss of employment opportunities (Copes et al., 2004; Abbott, Garber-Yonts, and Wilen, 2010), and loss of social capital, particularly among smaller operators and communities (McCay et al., 1995; Brandt, 2005; Carothers, 2015; Da-Rocha and Sempere, 2017).

Many of the concerns over distributional impacts derive from the tendency of ITQs to promote industry consolidation. ITQs have been found to promote consolidation of the fish harvesting sector in multiple empirical settings, including New Zealand

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(Yandle and Dewees, 2008; Abayomi and Yandle, 2012), Iceland (Eythórsson, 2000; Agnarsson, Matthiasson, and Giry, 2016), Canada (Casey et al., 1995; Dupont and Grafton, 2000), and the United States (Weninger, 1998; Warlick, Steiner, and Guldin, 2018). Consolidation in the harvest sector is likely to shift the distribution of economic and social benefits derived from the fishery from a widely dispersed set of fishermen to a smaller set. Regulated fishing firms are directly affected by these changes and are the unit of focus for the above studies.

Changes in behavior or outcomes at the firm level may also affect broader regional economies and communities, altering the location of fishing industry or causing dislocation in fishing ports and communities, particularly those that are relatively dependent on commercial fishing. Negative employment and income impacts in smaller communities are often cited as a concern both before and after ITQ policies are adopted (Olson, 2011; Russell et al., 2016). Geographic consolidation of the fishing sector can affect both the regional economy and local land use patterns of coastal communities through upstream and downstream linkages between industries related to fish harvesting (Portman, Jin, and Thunberg, 2009, 2011; Ounanian, 2015). Consolidation of landings and associated fishing infrastructure into fewer ports may also lower resilience of the fishing industry to anticipated changes in species distribution caused by climate change (Colburn et al., 2016; Hare et al., 2016).

Despite concern for the distributional impacts of ITQs on regional economies, the proposition that ITQ implementation induces a spatial redistribution of landings has rarely been tested quantitatively. Regional shifts in fishery landings have been observed following ITQs implemented in Canada (McCay et al., 1995), Alaska (McCay, 2004), and Iceland (Eythórsson, 2000), but changes in these cases could not be directly attributed to the policy. Similarly, Agnarsson, Matthiasson, and Giry (2016) use Gini coefficients and Lorenz curves to perform a simple comparison of the concentration of fishery landings in Iceland before and after ITQ implementation. They conclude that spatial distribution of landings was more concentrated in the post-ITQ period but that spatial concentration increased more slowly than industry consolidation. Bellanger, Macher, and Guyader (2016) compare differential changes in landings at a set of ports and use a decomposition of a Theil index to compare the spatial distribution of landings in France before and after catch-share implementation. Carothers, Lew, and Sepez (2010) analyze quota transfer patterns in Alaska and find that smaller communities were disproportionately affected by the ITQ program. Kuriyama et al. (2019) demonstrate that fleet consolidation (fewer vessels and trips) occurred following ITQ implementation in the U.S. West Coast Groundfish Trawl Fishery, the same fishery we analyze. Further, they examine at-sea fishing location and find no evidence that fishing became more spatially concentrated.

In this paper we ask whether the implementation of ITQs in 2011 induced a spatial redistribution of the limited-entry groundfish trawl fishery on the U.S. Pacific coast. Further, are we able to observe a pattern of spatial concentration where smaller fishing ports are disproportionately affected by industry consolidation? We use data before and after the implementation of transferable quotas as part of a catch-share program in 2011 in the limited-entry trawl fishery for groundfish in the U.S. Pacific Coast states of Washington, Oregon, and California. Our study is noteworthy in that we draw on concepts and specific measures of geographic distribution from the regional science and economic geography literatures. We also control for preexisting trends in port consolidation to assess the degree to which ITQ implementation may have altered the distribution of fishery benefits among fishing communities.

Measuring Geographic Distribution of Landings and Port Consolidation

We examine changes in the geographic distribution of landings before and after implementation of individual transferable quotas (ITQs) in the limited-entry groundfish trawl fishery on the U.S. Pacific Coast. Our work relies on the concepts of geographic concentration and intradistributional mobility.

Geographic concentration is the degree of disproportionality of the distribution of a sector of economic activity across a set of regions relative to a benchmark distribution (see Bickenbach and Bode, 2008, for a review of this concept and its measurement). Common benchmarks in the literature include a uniform distribution, which gives rise to absolute indices of concentration, and other sectors of economic activity (e.g., nongroundfish fisheries). Intuitively, high concentration indicates a geographic mismatch between the sector and the benchmark while a low degree of concentration would indicate geographical similarity of the sector and benchmark. Geographic concentration is a frequently studied phenomenon in regional science and economics. Explanations for concentration of economic activity tend to focus on economies of scale in combination with transport costs (Krugman, 1991), technical spillovers within (Romer, 1986) or between industries (Jacobs, 1985), spatial variation in government policies and regulations (Holmes, 1998), and geographical interpretations of comparative/natural advantages adapted from trade theory (Heckscher, Ohlin, and Samuelson, 1991; Fujita and Mori, 1996).

Intradistributional mobility within the spatial distribution of economic activity has been analyzed and tested for in the wider literature in regional science. In a series of papers, Quah (1993b,a, 1996) develops a Markov model of per capita income across countries that emphasizes the dynamics of full distributions rather than the dynamics of means and standard deviations. Lanaspa, Pueyo, and Sanz (2003) and Lanaspa and Sanz (2003) use Quah's methods to test for changes in the distributions of various industries rather than to test for cross-country income convergence. They first compare estimated density functions of industrial location quotients, then specify a Markov model and derive measures of mobility (i.e., variability in the relative distribution of economic activity across a landscape between periods). Desmet and Fafchamps (2006) test for changes in the spatial distribution of employment across U.S. counties over a 30-year interval. Their work also draws on Quah's methods as they test for σ-convergence and β-convergence, and they derive estimates of long-run trends in the change of a distribution, using transition matrices that cover periods of variable lengths. The emphasis in these previous studies is on describing long-run changes in the distribution of economic activity (e.g., employment) across a landscape. While we also evaluate changes in distribution, our emphasis is on detecting whether implementation of ITQs coincided with a reorganization of industrial activity across the landscape. Evaluating intradistributional changes in the geographic distribution of landings is important and represents a contribution of this paper. It allows us to identify shifts in landings between specific ports, even in ways that do not change the degree of geographic concentration. In fact, as our results will show, we find a high degree of intradistributional mobility in the revenue share of ports in periods around the policy change. This is evidence that implementation of ITQs may have induced shifts in landings between specific ports, though not in ways that increase geographic concentration. This analysis allows for a richer understanding of the distributional impacts of ITQs.

We use three methods to test for changes in the spatial distribution of this fishery: changes in the Theil index of spatial disproportionality, evaluation of kernel density functions of port-level revenue share, and analysis of Shorrocks index (SI) of intradistributional mobility. We calculate a time series of Theil index values to characterize trends in spatial concentration of the fishery over a 22-year period that encompasses periods before and after the policy change. We use parametric and nonparametric tests to assess whether observed increases in concentration are likely due to the policy change. We further examine changes in spatial concentration using kernel density estimators, where we find that increased concentration over time is driven by changes across the entire distribution. We measure the degree of intradistributional mobility in this system of ports using transition matrices and Shorrocks index of mobility.

Geographic Setting and Data

The setting for this study is the commercial limited-entry groundfish trawl fishery that harvests over 90 species of bottom-dwelling fish from waters off the Pacific Coast of the United States.[1] Vessels land fish at as many as 66 distinct locations throughout the coastal areas of the states of Washington, Oregon, and California. The Pacific Fishery Management Council is responsible for setting harvest regulations in the groundfish ITQ fishery, while the National Marine Fisheries Service is responsible for monitoring and enforcing those regulations. Fisheries policies are guided primarily by the Magnuson-Stevens Fishery Conservation and Management Act. In addition to preventing overfishing and achieving "optimum yield," the Act requires fishery managers to account for how regulations affect fishing communities when setting policy. Specifically, under National Standard 8 of the act, managers must utilize social and economic data to "(a) provide for the sustained participation of such communities, and (b) to the extent practicable, minimize adverse economic impacts on such communities" (Magnuson-Stevens Fishery Conservation and Management Act, 2007).

Harvest has been managed using multiple policy instruments, including annual catch limits, gear restrictions, closed areas, and closed seasons. Major historical policy changes include the implementation of limited access in 1994, rebuilding plans for several species that began in the late 1990s and continued to limit overall catch levels through the mid- and late 2000s, closure of the Rockfish Conservation Area to protect certain overfished species in 2003, and a buyback of trawl fishing vessels to reduce capacity in 2003. The ITQ program implemented in 2011 is the focus of this analysis. Various other economic effects of the implementation of this program have been studied elsewhere (Leonard and Steiner, 2017; Errend et al., 2018; Warlick, Steiner, and Guldin, 2018)

We use production data consisting of detailed landings receipts for all commercial fishery landings on the U.S. West Coast. Landings receipts, or fish tickets, are completed at the time a load of fish is sold and the entity purchasing the fish submits the information to state resource management agencies. Fish tickets are required for all fisheries in our study area and include the following important variables: vessel, port of landing, species, weight, price, and gear type. Fishermen in our study area participate in multiple fisheries. Each fishing trip is assigned to a fishery based on species composition, gear type, and permit type. Since 1981, the Pacific States Marine Fisheries Commission has managed the collection of landings receipt data as part of its Pacific Fisheries Information Network (PacFIN) program. We use data beginning in 1994, the first year in which limited entry (a cap on the number of fishing permits) was implemented in the groundfish fishery, through 2015.

We aggregate our data to the "port-fishery-year" level. The basic unit of analysis in our study is a fishing port. The complete set of PacFIN landings data contains 357 unique landing locations from 1994 to 2015. Of these, 66 had recorded landings in the groundfish ITQ fishery. Many of these landing locations are very small facilities (e.g., a small pier) or part of a larger port complex. We aggregate these landing locations to a set of 20 port complexes, hereafter referred to as "ports." Figure 1 shows areas covered by our port definitions. A Detailed description of our aggregation method is contained in the Online Supplement (available at www.jareonline.org).

The number of fishing vessels active in the limited-entry Pacific groundfish trawl fishery decreased by 70% from 1994 to 2015 (Figure 2). This decline in vessel participation has occurred consistently over the 22-year study period, though the most rapid phase was from 2002 to 2003, when 93 vessels exited the fishery as a result of a buyback program (Watson and Johnson, 2012; Holland, Steiner, and Warlick, 2017). The number of vessels participating in all other fisheries on the

[1] Three other fishing fleets harvest groundfish in our study area: a shore-based midwater trawl fishery for Pacific whiting, a fixed gear (pots and hook and line) fishery directed at sablefish, and an at-sea (mothership and catcher/processor) fishery for Pacific whiting. This analysis only examines changes in the observed geographic distribution of landings in the limited-entry trawl fishery for nonwhiting species, which is distinct from the other three, and which we will refer to as the "groundfish ITQ fishery."

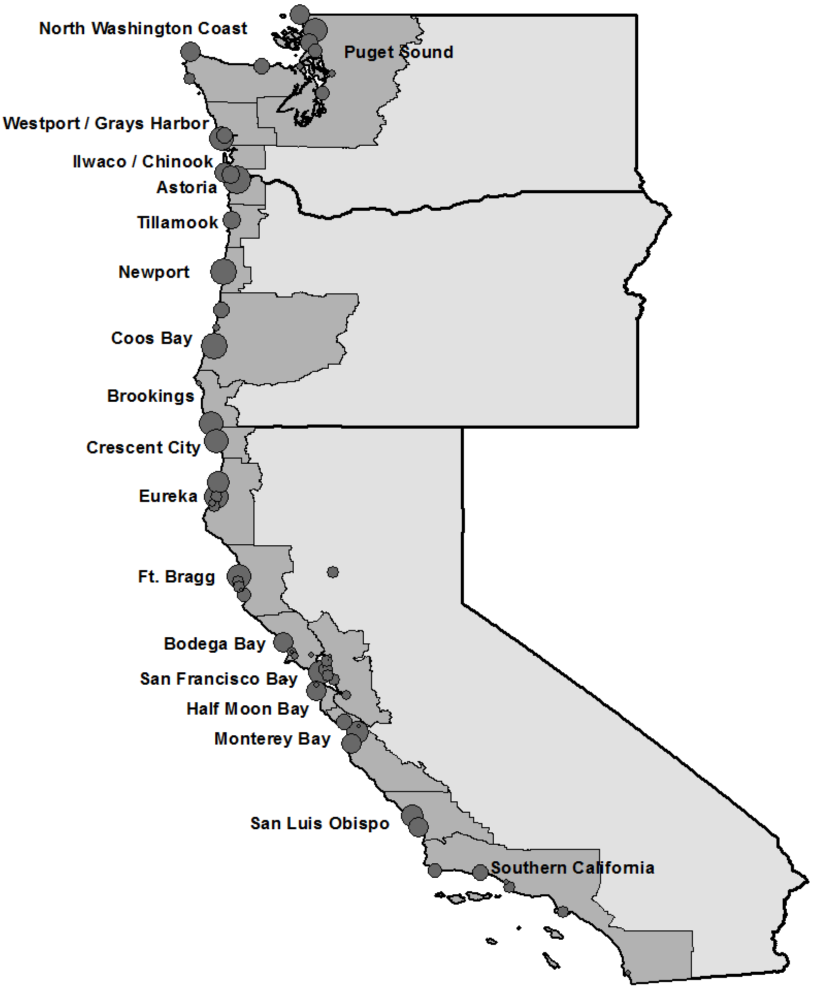

Figure 1. Map of the Study Area

Notes: Labeled polygons show the areas defined by our definition of 20 ports. Dots show the relative magnitudes of groundfish ITQ fishery revenue in the (in 2015 dollars) at each of 66 landing locations from 1994 to 2015.

U.S. West Coast also declined substantially (27%) over the entire study period, but participation in those fisheries rebounded from 2005 to 2015. Figure 2 shows that the value of the groundfish fishery declined precipitously from 1997 to 2003 and has remained at a much lower, though relatively stable, level since. This decline in is primarily due to lower catch levels as a result of stricter stock conservation measures beginning in the late 1990s.

Figure 3 shows the geographic distribution of *ex vessel* revenue in the groundfish ITQ fishery at specific points in time. Landings revenue has consistently been highest in northern and central Oregon in the ports of Astoria and Newport. Three ports from southern Oregon to northern California—Brookings, Eureka, and Fort Bragg—have experienced consistent and relatively high *ex vessel* revenue. Revenue in other ports appears more variable.

Table 1 presents total *ex vessel* revenue by port in the groundfish ITQ fishery for the 1994–2003 (pre-buyback), 2004–2010 (pre-ITQ), and 2011–2015 (post-ITQ) periods. The same ports constitute the five highest revenues in every period: Astoria, Coos Bay, Newport, Eureka, and Fort Bragg. Astoria is the highest revenue port in each period. Similarly, the eight lowest revenue ports are nearly the same in each period (with South Washington Coast and Crescent City moving out and in, respectively, in the post-ITQ period).

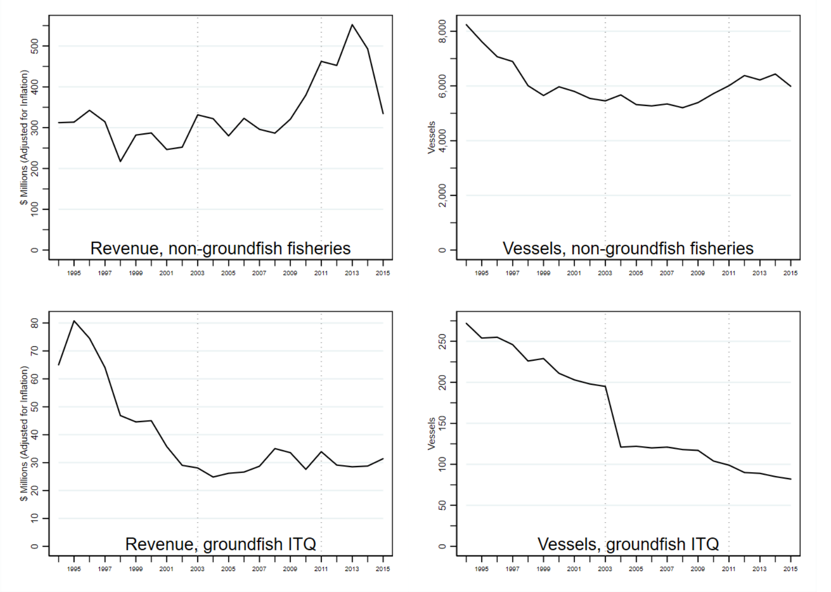

Figure 2. Active Fishing Vessels and Landings Revenue by Fishery, U.S. West Coast

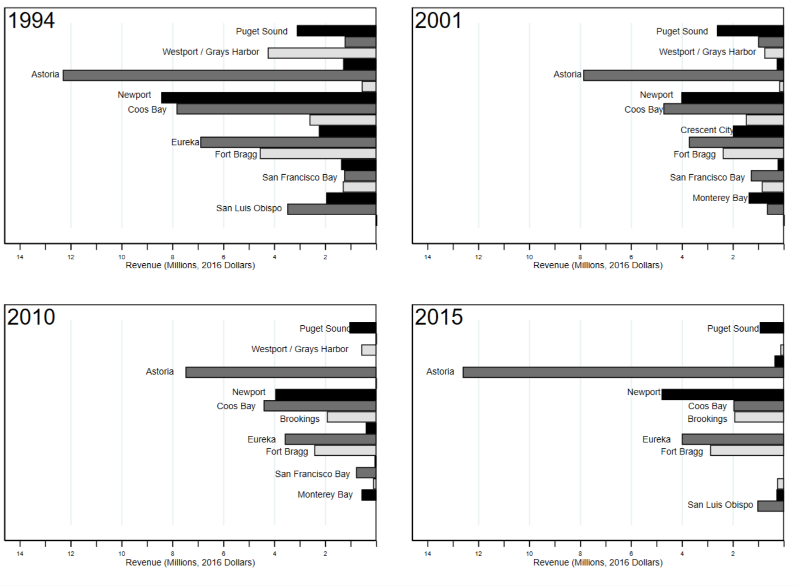

Figure 3. Distribution of *Ex Vessel* Revenue (2016 dollars), Groundfish ITQ Fishery 1994–2015

Notes: Ports ordered from north (top) to south (bottom). A vessel buyback was completed during 2003. ITQs were implemented beginning in 2011.

Table 1. ***Ex Vessel*** **Revenue by Port, West Coast Groundfish ITQ Fishery**

Port	Revenue All Years ($2016)	Port Proportion of Total Groundfish ITQ Fishery Revenue All Years (%)	1994–2003 (%)	2004–2010 (%)	2011–2015 (%)
Astoria	209,480,280	24	19	28	36
Coos Bay	111,084,847	13	13	14	8
Newport	100,852,683	11	11	13	12
Eureka	97,630,741	11	11	12	12
Fort Bragg	68,592,163	8	8	8	8
Brookings	41,323,006	5	4	5	7
Puget Sound	38,446,410	4	5	5	3
Crescent City	35,887,790	4	6	3	1
San Luis Obispo County	34,406,948	4	5	1	4
Monterey Bay	31,861,711	4	5	3	2
Westport/GrayâĂŹs Harbor	29,632,164	3	5	2	1
San Francisco Bay	26,498,706	3	3	3	1
Ilwaco/Chinook	15,256,683	2	1	0	5
North Washington Coast	14,792,390	2	3	1	0
Half Moon Bay	14,008,186	2	2	1	1
Bodega Bay	11,207,972	1	2	0	0
Tillamook	2,851,189	0	1	0	0
Southern California	38,020	0	0	0	0
Other California ports	17,755	0	0	0	0
Other Washington ports	10,891	0	0	0	0

Methods

Theil Index of Spatial Concentration

A concentration index characterizes the amount of disproportionality, compared to a reference, in the distribution of industrial activity (groundfish fishery revenue) across mutually exclusive regions (ports). Many different types of aggregation functions, weightings, and reference distributions have been used to examine industrial concentration (see Bickenbach and Bode, 2008, for an extensive discussion). We use a Theil aggregation function and weight each port equally. We employ two reference distributions. First, we use a uniform distribution to construct an "unweighted absolute" Theil index. This index defines "no concentration" as an equal distribution of groundfish revenue across ports. Second, we use the distribution of nongroundfish *ex vessel* revenue as a reference distribution to construct an "unweighted relative" index. The relative Theil index defines "no concentration" as groundfish value proportional to nongroundfish revenue. Therefore, the relative Theil index to some extent controls for factors affecting commercial fishing industry as a whole; any observed changes would be due to factors affecting only (or at least disproportionately) the groundfish fishery.

We develop our absolute and relative Theil indices for spatial disproportionality of port-level revenue in the U.S. Pacific Coast groundfish fishery from the general forms in Bickenbach and Bode (2008). Let p index individual ports and P be the total number of ports along the coast. Let f index individual fisheries, which can take on two values: $f = G$ for the groundfish ITQ fishery and $f = N$ for all other nongroundfish fisheries.[2] We are interested in changes in the distribution of landings over time and calculate an index value for each year in the study period, indexed by t. Let $L_{p,f,t}$ denote the revenue landed at port p in fishery f in year t and $L_{f,t}$ denote the total coastwide revenue

[2] "All other nongroundfish fisheries" does not include the other three fleets described in footnote 1.

landed in fishery f in year t. We calculate the absolute Thiel index for the groundfish ITQ fishery:

$$\lambda_{p,G,t} = \frac{L_{p,G,t}}{L_{G,t}}; \tag{1}$$

$$T_{GF,absolute} = \sum_{p=1}^{P} \lambda_{p,G,t} ln\left(P\lambda_{p,G,t}\right); \tag{2}$$

where $L_{p,G,t}$ denotes the revenue landed at port p in the groundfish ITQ fishery in year t and $\lambda_{p,G,t}$ is the share of coastwide groundfish revenue landed at port p in year t. Equation (2) is the absolute Theil index for the groundfish ITQ fishery in year t.

We then calculate the relative Thiel index for the groundfish ITQ fishery, with landings in all other nongroundfish fisheries as the reference distribution:

$$l_{p,G,t} = \frac{L_{p,G,t}}{L_{p,G,t} + L_{p,N,t}}; \tag{3}$$

$$T_{GF,relative} = \sum_{p=1}^{P} \frac{l_{p,G,t}}{\sum_p l_{p,G,t}} ln\left(P\frac{l_{p,G,t}}{\sum_p l_{p,G,t}}\right); \tag{4}$$

where $l_{p,G,t}$ is the ratio of groundfish ITQ revenue to combined revenue in the groundfish ITQ and reference distribution fisheries (i.e., all nongroundfish fisheries) at port p in time t.

To test whether any observed changes in the disproportionality index are likely to be caused by the implementation of ITQs, we conduct falsification tests that compare the magnitude of observed changes coincident with policy implementation to observed changes in periods with no policy change.

Kernel Estimated Revenue Share Distributions

While the Theil indices summarize industry-level geographical concentration trends, examination of the complete empirical distribution can provide more insight into the forces shaping concentration. To visualize the geographic concentration of the groundfish ITQ fishery on the U.S. West Coast, we estimate the density function of the geographic distribution of fishery landings over several periods.

We plot the share of revenue landed in each port for the groundfish ITQ fishery and, for comparison, other nongroundfish fisheries. The distribution of these values is a measure of concentration of landings revenue among the set of ports. If fishery-specific landings are exactly evenly dispersed across ports (a uniform distribution), then each port would have a revenue share of 0.05, (because there are 20 ports) for a given fishery. If landings are highly concentrated in a few ports, then each port will have values very different from 0.05, with some ports having values approaching 1 and some having values at or near 0. To see how the level of geographic concentration has changed over time, we can compare the distribution of revenue share values across periods.

Intradistributional Mobility

Evaluation of differences in the shapes of density functions and changes in the Theil disproportionality index over time allowed us to evaluate whether fishery landings became more concentrated in larger ports. Those analyses, however, do not have the ability to track the intradistributional, or cross-sectional, dynamics of individual ports. That is, identical sets of share values reordered among ports are treated as no change in distribution. To address this, we evaluate transitions between the distributions of port-level revenue in different periods. Our analysis of intradistributional dynamics is similar to models that have been applied to test for changes in geographic distribution of industrial activity (e.g., Lanaspa and Sanz, 2003; Desmet and Fafchamps,

2006) and convergence in country-specific ecological outcomes (Pennino et al., 2017). We use a Markov chain framework to estimate transition matrices and SI values to measure changes in the geographic distribution of landings across periods.

A finite Markov chain describes a population with a distribution (F_t) over discrete states $\{S_1, \dots, S_n\}$ at time t. Further, the probability of a member of the population transitioning from state S_i at time t to state S_j at time $t+1$ depends only on the initial state S_i in period t (and not on any state prior to t). We denote the cross-sectional distribution of *ex vessel* revenue across our system of ports at time t as F_t. This distribution in the following period is then

$$F_{t+1} = M \times F_t, \tag{5}$$

where M describes how the distribution F_t moves from one cross section to another. This equation is analogous to a first-order autoregressive equation, except that the terms are distributions, rather than scalars (or vectors of numbers) (Quah, 1993b,a).

We estimate five-state Markov chain models for the distribution of port share of *ex vessel* revenue. One state is a share of 0 (i.e., no ITQ groundfish landings at a port in a given year). Another state is revenue share greater than the minimum observed at Astoria, Oregon (0.1635), which is the highest-revenue port in every year of the study period. We discretize the remaining port share values (for all 22 years in the study period) into three equal-sized states, with breakpoints at 0.0216, 0.0562, and 0.1635. We then estimate a transition probability matrix ($\boldsymbol{M}$) where the dimension of $\boldsymbol{M}$ is the number of states in the state space (5×5 in our case). We define each state as a port's presence in one of the five bins of the distribution of port share of groundfish ITQ landings revenue. Each cell of the matrix $\boldsymbol{M}(i, j)$ contains the proportion of ports in a the ith state in the initial period that switch to jth state in the next period. These transition probabilities are estimates of the probability of any given port transitioning between two states.

The five states are arranged in increasing order along the rows and columns of $\boldsymbol{M}$. Transition matrices used in the analysis are found in the supplemental material. So, the upper left corner shows the proportion of ports with 0 landings at time t that also had 0 landings at time $t+1$. Note then, that the diagonal of $\boldsymbol{M}$ represents the percentage of ports that remained in the state from t to $t+1$. High values on the *diagonal* of $\boldsymbol{M}$ indicate a high degree of *stability* in the distribution from one period to another. *High* values in the *off-diagonal* cells of $\boldsymbol{M}$ indicated a high degree of *mobility* in the distribution. Put another way, no change in the distribution would produce a transition matrix that is the identity matrix. Conversely, a complete redistribution of landings revenue would produce a transition matrix with zeros on the diagonal.

$\boldsymbol{M}$ is a matrix that characterizes the mobility within a distribution (intradistributional dynamics) (i.e., how much of one part of the distribution moves to another part over time). We can calculate a scalar index of mobility that condenses the information in $\boldsymbol{M}$. Shorrocks (1978) first used an index to characterize individuals' mobility within national income distributions. We can apply it here to characterize shifts in landings revenue between ports:

$$SI(\boldsymbol{M}) = [dim(\boldsymbol{M}) - trace(\boldsymbol{M})]/[dim(\boldsymbol{M}) - 1], \tag{6}$$

where $dim(\boldsymbol{M})$ is the number of states in the Markov chain (5 in our case) and $trace(\boldsymbol{M})$ is the sum of the elements on the main diagonal of $\boldsymbol{M}$.

We test for whether intradistributional mobility may have been a result of the policy change by conducting falsification tests where we calculate SI index values for each of many transitions. Falsification tests compare the magnitude of observed changes coincident with policy implementation to observed changes in periods with no policy change.

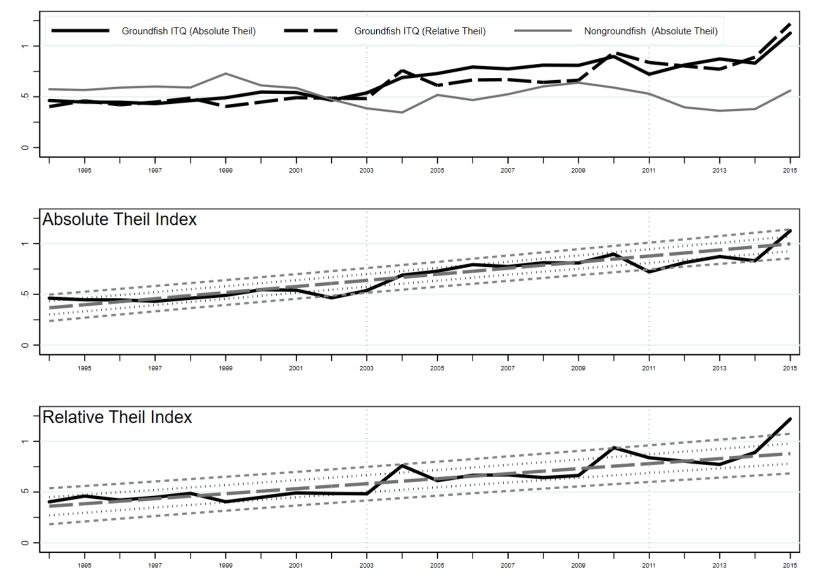

Figure 4. Theil Index of Disproportionality

Notes: The top panel includes the absolute Theil index, with disproportionality in the groundfish ITQ and nongroundfish fisheries measured relative to a uniform distribution, and the relative Theil index, with disproportionality for the groundfish ITQ measured relative to the distribution of landings revenue in nongroundfish fisheries in the same year. The middle panel is the absolute Theil index for the groundfish ITQ fishery. The bottom panel is the relative Theil index for the groundfish ITQ fishery. Observed Theil Index values in the middle and bottom panels are plotted with the 95% confidence interval and one standard deviation generated from a regression of each index on a linear time trend for the pre-ITQ time period (1994–2010). Intervals are calculated using the standard error of the forecast value.

Results

Change in the Theil Index over Time

Figure 4 shows trends in spatial concentration in the ITQ groundfish fishery from 1994–2015. Four of the 5 years in the post-ITQ period (2011–2015) rank among the highest five absolute spatial concentration values, with 2015 having the highest Theil index value and 2011 having only the 11th highest. Only 1 year prior to ITQs implementation has a spatial concentration value in the top five, but it is 2010—the year immediately preceding ITQ implementation—and has the second-highest value. This indicates that the groundfish ITQ fishery contracted geographically, in absolute terms, following implementation of ITQs.

We compare trends in geographic concentration in the groundfish ITQ fishery to all other nongroundfish fisheries, which were not affected by the policy change. The relative Theil index controls for factors that may have affected the commercial fishing industry generally and are unrelated to implementation of ITQs in the groundfish fishery. Five of the six highest relative Theil index values occur in the 5 years in the post-catch-share period, with the last year in the time series, 2015, having the highest value. This suggests that the ITQ groundfish fishery contracted geographically, relative to the distribution of nongroundfish fisheries, following the implementation of ITQs.

However, this increase in concentration index levels appears to be part of a long-term trend that dates to the beginning of the study period in 1994. Figure 4 (middle and bottom panels) plots the absolute and relative concentration indices along with a trend line estimated with data from the pre-ITQ period (1994–2010), including the estimated standard deviation and 95% confidence interval. For the absolute Theil index, concentration index levels are below the forecasted trend in the 4 years immediately following ITQ implementation, suggesting that the fishery became more geographically dispersed following ITQs, when compared to preexisting trends. The exception is 2015, when the concentration index increased substantially to end up above the forecasted trend line. Similarly, for the relative Theil index, the observed concentration index values are within 1 standard deviation of the forecasted trend for the first 4 years after ITQ implementation. This again suggests that observed geographic contraction in the groundfish ITQ fishery (relative to nongroundfish fisheries) was not necessarily due to the ITQ program.

We test whether observed increases in concentration over time are distinct from preexisting trends and thus likely to be caused by ITQ policy implementation by conducting falsification tests. These tests compare the magnitude of changes in Theil index values over periods affected by the policy change to observed changes over periods that are known to be unaffected. We can observe changes in the Theil index value that occur over multiple periods (e.g., over a 1-year period, a 2-year period, etc.). Because of the length of the time series (22 years, 1994–2015) and the placement of the policy change (2011), observing transitions over 1-, 2-, 3-, 4-, and 5-year periods will give us five sets of transitions for which we can compare mobility in periods that do and do not cover the policy change. For example, analyzing changes over 5-year periods allows us to observe 17 total transitions, with five transitions covering the implementation of ITQs (2006–2011, 2007–2012, 2008–2013, 2009–2014, 2010–2015) and 12 transitions that occur over periods during which the policy change does not occur. Positive values indicate that landings revenue become more concentrated in fewer ports over the period analyzed. If the implementation of the ITQ program induced an increase in the concentration of landings revenue among ports, then we expect that the observed changes in the Theil index will be high relative to other values calculated over periods where no policy change occurred.

Figure 5 shows the distribution of observed changes in absolute and relative Theil index values for the groundfish ITQ over sets of 1-, 2-, 3-, 4-, and 5-year periods. Boxes contain the observed distribution of index values that are less than the *n* most extreme values, where *n* is the number of transitions that occur between the pre-ITQ period (1994–2010) and the post-ITQ period (2011–2015). Whiskers mark the maximum and minimum observed values. "X" indicates a transition that occurs between pre- and post-ITQ periods. Positive values indicate that landings revenue become more concentrated in fewer ports over the period analyzed. In both the absolute and relative Theil index, periods affected by the policy change do not appear to be larger in general than the unaffected periods (see the top and bottom panels of Figure 5, respectively). Across all five sets of transitions (and including both absolute and relative Theil index values) nine out of 30 of the potentially policy-impacted changes are among the *n* largest changes observed and 16 are among the *n* smallest changes observed. This again suggests that observed changes in geographic distribution are relatively similar across all years and that spatial contraction in the ITQ groundfish fishery was not necessarily due to the ITQ program.

Empirical Kernel Density of Port Revenue Share

Figure 6 is the estimated density function for revenue shares in the groundfish ITQ fishery and other nongroundfish fisheries on the U.S. West Coast. The density functions are estimated using an Epanechnikov kernel function with bandwidth selected using the plug-in method proposed by Sheather and Jones (1991). For each fishery, landings revenue is aggregated over three 5-year periods: 1998–2002 (preceding a groundfish vessel buyback in 2003), 2006–2010 (preceding implementation of ITQs in the groundfish ITQ fishery in 2011), and 2011–2015 (the 5 years following ITQs). We can draw three conclusions by examining Figure 6. First, the groundfish ITQ fishery is more geographically concentrated than other nongroundfish fisheries. A large portion of the revenue share distribution for the groundfish ITQ is at or near 0. This means that many ports land a small fraction of the revenue in these fisheries, with many ports having 0 landings. Therefore, the remaining revenue (a comparatively large fraction) is landed in the few remaining ports. Second, the distribution of revenue in the groundfish ITQ fishery has become more geographically concentrated

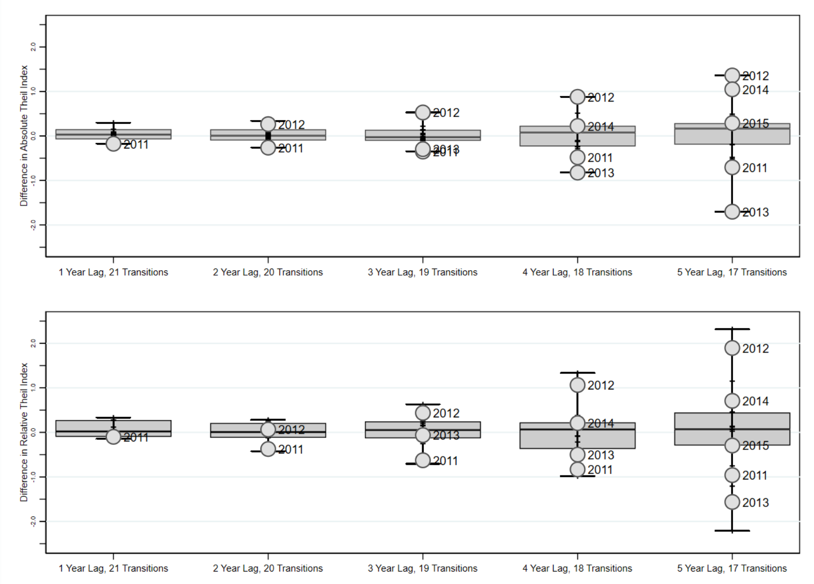

Figure 5. Distribution of Observed Changes in Concentration of Landings Revenue among Ports for the Groundfish ITQ Fishery, as Indicated by Absolute and Relative Theil Indices

Notes: Boxes contain the observed distribution of index values that are less than the *n* most extreme values, where *n* is the number of transitions that occurs between the pre-ITQ period (1994–2010) and the post–ITQ period (2011-2015). Whiskers mark the maximum and minimum observed values. "O" indicates a transition that occurs between pre- and post-ITQ periods. Positive values indicate that landings revenue become more concentrated in fewer ports over the time period analyzed.

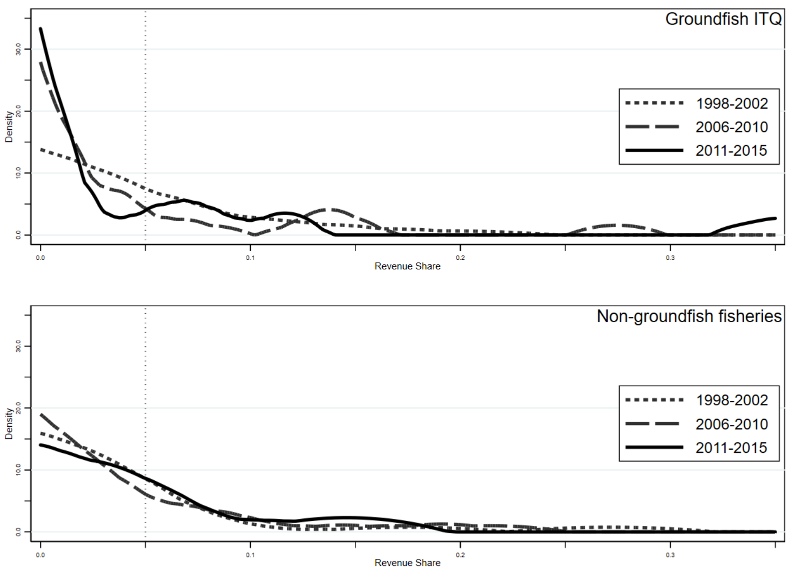

Figure 6. Estimated Density Functions of Revenue Shares for the Groundfish Trawl ITQ and Other Nongroundfish Fisheries

Notes: Calculated over three periods: before industry consolidation occurring after a vessel buyback in 2003, 5 years immediately prior to implementation of the ITQ program, and 5 years following the implementation of the ITQ program in 2011. Densities estimated using the Epanechnikov kernel with bandwidths varying by time period.

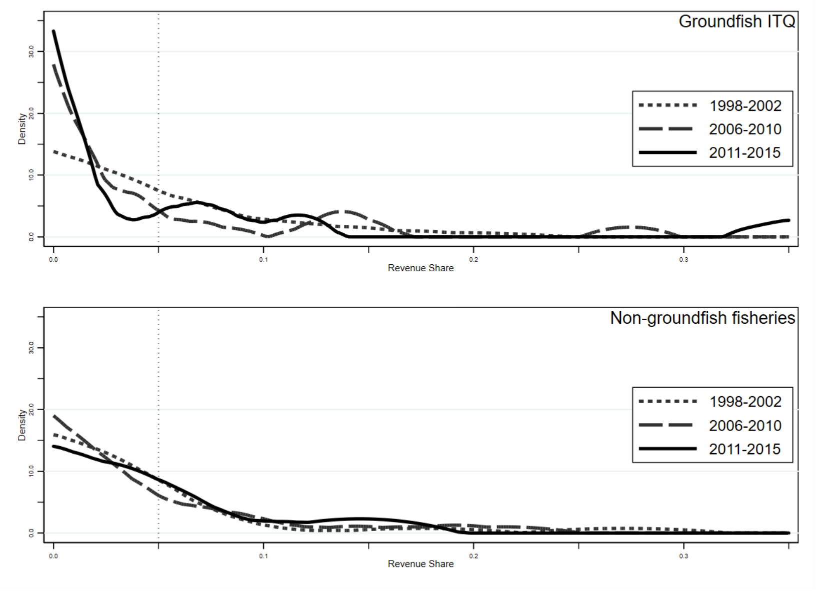

Figure 7. Distribution of Observed Intradistributional Mobility Values for the Groundfish ITQ Fishery, as Indicated by Shorrocks Index

Notes: Boxes contain the observed distribution of index values that are less than the *n* most extreme values, where *n* is the number of transitions that occurs between the pre-ITQ period (1994–2010) to the post-ITQ period (2011–2015). Whiskers mark the maximum and minimum observed values. "Diamond" indicates a transition that occurs between pre- and post-ITQ periods.

over time, consistent with the results of plotting the concentration indices over time above. Much of this change in concentration occurred between the first and second periods of the analysis; that is, following implementation of a groundfish vessel buyback in 2003 (Watson and Johnson, 2012). Third, following implementation of ITQs in 2011, the distribution of revenue shifted such that (i) very small ports landed a reduced share of landings, as mass shifted toward 0, and (ii) more ports were landing an intermediate share of revenue as mass shifted away from a hump at about 0.14 and toward shares of 0.06–0.12. This second shift also coincides with revenue share shifting toward a single very large port (Astoria, see Table 1).

Shorrocks Index and Transitions around the Policy Change

We conduct falsification tests in a manner similar to that described for the change in Theil index values. We calculate transition matrices and the resultant SI index of mobility for each of many transitions over 1-, 2-, 3-, 4-, and 5-year periods. If the calculated mobility values for transitions that cover the policy change are generally larger than those that do not, then we consider that evidence that the policy change induced the change in distribution.

Figure 7 shows the distribution of observed intradistributional mobility values for the Groundfish ITQ fishery. Higher SI values indicate higher mobility; in our case we interpret this as a greater change in the distribution of landings revenue among ports between two periods. Boxes contain the observed distribution of index values that are less than the *n* most extreme values, where *n* is the number of transitions that occurs between the pre-ITQ period (1994–2010) to the post-ITQ period (2011–2015). For example, in the case of 5-year transitions, we observe five transitions covering the implementation of ITQs. Values outside the boxes are one of the highest (or lowest) 5 values observed. Whiskers mark the maximum and minimum observed values. "O" indicates a transition that occurs between the pre-ITQ period (1994–2010) to the post-ITQ period (2011–2015).

Figure 7 shows that calculated mobility values for transitions covering the implementation of the ITQ program are among the largest observed over the entire study period. Ten out of 14 transitions that occur over a period covered by the policy change among the *n* greatest values in the time series of SI values. Further, none of the observed policy-coincident transitions were among the *n* lowest intradistributional mobility values. This provides evidence that the implementation of ITQs resulted in changes in the distribution of landings revenue across ports.

Examining the transition matrices for these periods (see the Online Supplement) shows that that these high-mobility values were driven by some very specific dynamics. First, two ports, the Ilwaco/Chinook region in southern Washington and San Luis Obispo County in California, went from 0 landings in 2010 to over 8% of landings in the groundfish ITQ fishery in 2011. In both cases, this appears to have a been a systematic change since San Luis Obispo averaged about 0.5% of landings from 2006 to 2009 and the South Washington Coast had recorded 0 groundfish ITQ landings in 6 out of 8 years from 2003 to 2010 and had not exceeded 1% of fishery revenue since 1999. Second, San Francisco Bay declined from about 2.5%–5% of fisheries landings (within state three of the transition matrices) to 0%–2.8% of landings from 2011 to 2015 (within states one, two, and three). Third, three ports—Tillamook, the North Washington Coast region, and Bodega Bay—dropped from <1% of revenue to 0 landings.

Conclusion

Our goal has been to evaluate whether implementing a policy of rights-based management (ITQs) induced a change in the geographic distribution of production in a fishery. We find evidence that geographic concentration of fishing revenue across ports increased over the period following policy implementation. Specifically, the density of port-level revenue shares shifted, with more mass moving to the tails of the distribution, more ports recording 0 or very low levels of production, and the largest port accounting for an increasing share of fishery revenue. Further, the Theil index of disproportionality in measuring the level of concentration increased somewhat after policy implementation. However, these changes appear to be indistinguishable from preexisting trends in the groundfish ITQ fishery. Plots of linear trends in disproportionality values and falsification tests of changes in Theil index values indicate that concentration changes are consistent with changes that may have occurred under preexisting trends.

Our analysis of intradistributional changes showed evidence of a high degree of change in the distribution of landings revenue concurrent with the policy change. We observe high Shorrocks index of mobility values for transitions covering the implementation of ITQs in 2011 relative to periods with no policy change. We can attribute a good deal of this distributional change to changes at specific ports based on analysis of specific cells in our transition matrices. These intradistributional changes occur among both larger and smaller ports, and so we cannot conclude that intradistributional shifts are related to port size. For example, while Astoria was the highest-revenue port in each year, Coos Bay—the second-highest value port across all years—declined in terms revenue share and relative position. Some small- to medium-sized ports, such as San Luis Obispo County, South Washington Coast, and Bodega Bay also saw substantial changes. This analysis of intradistribution mobility indicated that ITQ implementation likely had some impact on the geographic distribution of landings, but that the effect was likely not consolidation into fewer ports. This indicates that more investigation, using different methods, is needed to identify specific drivers of port-specific changes. Examples of these port-specific factors could be differences in infrastructure, institutional arrangements between harvesters and buyers, or operational characteristics of specific firms. Our methods are designed to identify potential unequal effects among communities of different sizes that could be due to economies of scale and scope but are unable to identify drivers at specific ports.

In evaluating policy impacts, individual firms are the most obviously affected entities. However, communities dependent on the economic base generated by regulated industries also feel economic effects via upstream and downstream linkages. This is especially true in many smaller communities dependent on natural-resource-based industries. A primary concern with transferable fishing quotas in general has been that increased industry consolidation will mainly reduce economic activity in smaller communities as the remaining components of the fishing industry will operate out of larger ports. In the case of the U.S. West Coast groundfish ITQ fishery, our evidence on this point is mixed. On one hand, we observe geographic distribution concentrating in the largest port, several smaller ports dropping out of the fishery, and one important midsized port reduce its share (see our kernel port share distributions and analysis of specific transitions). On the other hand, our Theil index of disproportionality is unable to detect any concentration effects that differ from preexisting trends. In addition, two ports went from 0 or a very small proportion of the fishery to a sizeable share following policy implementation, which is evidence of deconcentration.

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Online Supplement: Geographic Distribution of Commercial Fishing Landings and Port Consolidation following ITQ Implementation

Cameron Speir and Min-Yang Lee

Port Aggregation Methods

We describe in detail our aggregation of 357 specific landings locations to 20 ports used in our analysis. This is reported in this appendix in Table S1. Our aggregation scheme preserves functional port units and encompasses all fish landed on the US west coast. To aggregate to our 20 ports, we begin with a list of all 357 reported locations on in PacFIN fish ticket data. This list is contained in the APR table "Agency/PacFIN port relationship data" in the PacFIN database. PacFIN aggregates these landings sites to 84 "Port-Country IDs", or groups of related landings sites along the coast of Washington, Oregon and California. The APR table and PCID definitions can be viewed at (https://pacfin.psmfc.org/pacfin_pub/data_rpts_pub/code_lists/agency_ports.txt).

We also compare our port aggregation scheme to the a similar aggregation scheme used in the Input-Output Model for Pacific Coast Fisheries (IOPAC), used by NOAA Fisheries to estimate the sub-regional economic impacts of fishery management measures (Leonard and Watson, 2011). The IOPAC model aggregates PCIDs to 19 port complexes. That grouping is defined in Leonard and Watson (2011, see Table 9 p. 29–30).

Our scheme is concordant with IOPAC in the case of 14 port-complexes: Puget Sound, North Washington Coast, Astoria, Tillamook, Newport, Coos Bay, Brookings, Crescent City, Eureka, Fort Bragg, Bodega Bay, Morro Bay, Other California, and Other Washington. Differences between our aggregation and the IOPAC complexes are:

1. We aggregate all ports south of Morro Bay, California into a single complex: "Southern California." This is because of the relatively low volume and small number of ports that historically landed groundfish in the ITQ fishery.

2. We include many additional ports not reported as included in the IOPAC model aggregation. This is due to the extended time period of our analysis, which begins in 1994. IOPAC analysis began in 2004. In the years between 1994 and 2004, many ports ceased landing fish.

3. Our aggregation has increased spatial resolution (i.e., a greater number of port regions) in central California and the Washington coast. Specifically, we include the port of Half Moon Bay, California, which lands a significant proportion of the groundfish ITQ fishery revenue and is functionally distinct from San Francisco (see Table 1 in the main text). We also separate the central Washington coast into the ports of "Westport/Central Washington Coast" and "South Washington Coast". These two ports are functionally distinct and each land a significant proportion of the groundfish ITQ fishery. South Washington contains the important port of Ilwaco.

References

Leonard, J., and P. Watson. 2011. Description of the Input-Output Model for Pacific Coast Fisheries. Washington, DC: U.S. Department of Commerce, NOAA Technical Memo NMFS-NWFSC-111.

Table S1. Aggregation from Port Communities to PacFIN PCIDs to IOPAC Port Complexes to Ports Used in the Current Study

State	Location	PCID	IOPAC Complex	Port (Current Study)
Washington	ANACORTES	ANA	Puget Sound	Puget Sound
Washington	BELLINGHAM BAY	BLL	Puget Sound	Puget Sound
Washington	BLAINE	BLN	Puget Sound	Puget Sound
Washington	BREMERTON	OSP		Puget Sound
Washington	BRINNON	OSP		Puget Sound
Washington	CENTRALIA/CHEHALIS	OWA		Puget Sound
Washington	COUPEVILLE	ONP	Puget Sound	Puget Sound
Washington	DEER HARBOR	ONP	Puget Sound	Puget Sound
Washington	EVERETT	EVR	Puget Sound	Puget Sound
Washington	FRIDAY HARBOR	FRI	Puget Sound	Puget Sound
Washington	LACONNER	LAC	Puget Sound	Puget Sound
Washington	MARIETTA	BLL	Puget Sound	Puget Sound
Washington	OLYMPIA	OLY	Puget Sound	Puget Sound
Washington	POINT ROBERTS	ONP	Puget Sound	Puget Sound
Washington	PORT TOWNSEND	TNS	North WA coast	Puget Sound
Washington	POULSBO	OSP		Puget Sound
Washington	QUILCENE	OSP		Puget Sound
Washington	SEATTLE	SEA	Puget Sound	Puget Sound
Washington	SHELTON	SHL	Puget Sound	Puget Sound
Washington	STANWOOD	ONP	Puget Sound	Puget Sound
Washington	TACOMA	TAC	Puget Sound	Puget Sound
Washington	WHIDBY ISLAND	ONP	Puget Sound	Puget Sound
Washington	HOH	OWC		North WA Coast
Washington	LAPUSH	LAP	North WA coast	North WA Coast
Washington	NEAH BAY	NEA	North WA coast	North WA Coast
Washington	PORT ANGELES	PAG	North WA coast	North WA Coast
Washington	QUEETS	OWC		North WA Coast
Washington	QUILLAYUTE	OWC		North WA Coast
Washington	SEQUIM	SEQ	North WA coast	North WA Coast
Washington	ABERDEEN	GRH	South and central WA coast	Westport/Central WA Coast
Washington	BAY CITY	GRH	South and central WA coast	Westport/Central WA Coast
Washington	COPALIS BEACH	CPL	South and central WA coast	Westport/Central WA Coast
Washington	GRAYLAND	OWC		Westport/Central WA Coast
Washington	HOQUIAM	GRH	South and central WA coast	Westport/Central WA Coast
Washington	OAKVILLE	GRH	South and central WA coast	Westport/Central WA Coast
Washington	TAHOLAH	OWC		Westport/Central WA Coast
Washington	WESTPORT	WPT	South and central WA coast	Westport/Central WA Coast
Washington	BAY CENTER	WLB	South and central WA coast	S WA Coast/Col R
Washington	CAMAS	OCR	South and central WA coast	S WA Coast/Col R
Washington	CATHLAMET	OCR	South and central WA coast	S WA Coast/Col R
Washington	CHINOOK	LWC	South and central WA coast	S WA Coast/Col R
Washington	COLUMBIA RIVER PORTS − OREGON	CRV		S WA Coast/Col R
Washington	GRAY'S BAY	OCR	South and central WA coast	S WA Coast/Col R
Washington	ILWACO	LWC	South and central WA coast	S WA Coast/Col R
Washington	KALAMA	OCR	South and central WA coast	S WA Coast/Col R
Washington	KELSO	OCR	South and central WA coast	S WA Coast/Col R
Washington	LONG BEACH	OWC		S WA Coast/Col R
Washington	LONGVIEW	OCR	South and central WA coast	S WA Coast/Col R
Washington	NAHCOTTA	WLB	South and central WA coast	S WA Coast/Col R
Washington	NASELLE	WLB	South and central WA coast	S WA Coast/Col R
Washington	PACIFIC COUNTY	OCR	South and central WA coast	S WA Coast/Col R
Washington	PUGET ISLAND	OCR	South and central WA coast	S WA Coast/Col R
Washington	RAYMOND	WLB	South and central WA coast	S WA Coast/Col R
Washington	RIDGEFIELD	OCR	South and central WA coast	S WA Coast/Col R
Washington	SKAMANIA	OCR	South and central WA coast	S WA Coast/Col R
Washington	SKAMOKAWA	LWC	South and central WA coast	S WA Coast/Col R
Washington	SOUTH BEND	WLB	South and central WA coast	S WA Coast/Col R

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Table S1. – continued from previous page

State	Location	PCID	IOPAC Complex	Port (Current Study)
Washington	STELLA	OCR	South and central WA coast	S WA Coast/Col R
Washington	THE DALLES	OCR	South and central WA coast	S WA Coast/Col R
Washington	TOKELAND	WLB	South and central WA coast	S WA Coast/Col R
Washington	VANCOUVER	OCR	South and central WA coast	S WA Coast/Col R
Washington	WASHOUGAL	OCR	South and central WA coast	S WA Coast/Col R
Oregon	ASTORIA	AST	Astoria	Astoria
Oregon	CANNON BEACH	CNB	Astoria	Astoria
Oregon	GEARHART-SEASIDE	GSS	Astoria	Astoria
Oregon	GARIBALDI (TILLAMOOK)	TLL	Tillamook	Tillamook
Oregon	NEHALEM BAY	NHL	Tillamook	Tillamook
Oregon	NETARTS	NTR	Tillamook	Tillamook
Oregon	PACIFIC CITY	PCC	Tillamook	Tillamook
Oregon	DEPOE BAY	DPO	Newport	Newport
Oregon	NEWPORT	NEW	Newport	Newport
Oregon	SALMON RIVER	SRV		Newport
Oregon	SILETZ BAY	SLZ		Newport
Oregon	WALDPORT	WLD	Newport	Newport
Oregon	YACHATS	YAC		Newport
Oregon	BANDON	BDN	Coos Bay	Coos Bay
Oregon	CHARLESTON (COOS BAY)	COS	Coos Bay	Coos Bay
Oregon	FLORENCE	FLR	Coos Bay	Coos Bay
Oregon	WINCHESTER BAY	WIN	Coos Bay	Coos Bay
Oregon	BROOKINGS	BRK	Brookings	Brookings
Oregon	GOLD BEACH	GLD	Brookings	Brookings
Oregon	PORT ORFORD	ORF	Brookings	Brookings
California	CRESCENT CITY	CRS	Crescent City	Crescent City
California	KLAMATH	ODN		Crescent City
California	REQUA	ODN		Crescent City
California	SMITH RIVER	ODN		Crescent City
California	ARCATA	OHB	Eureka	Eureka
California	BLUE LAKE	OHB	Eureka	Eureka
California	CRANNELL	OHB	Eureka	Eureka
California	EUREKA	ERK	Eureka	Eureka
California	EUREKA AREA	ERK	Eureka	Eureka
California	FERNDALE	OHB	Eureka	Eureka
California	FIELDS LANDING	FLN	Eureka	Eureka
California	FORTUNA	OHB	Eureka	Eureka
California	GARBERVILLE	OHB	Eureka	Eureka
California	HUMBOLDT	OHB	Eureka	Eureka
California	KING SALMON	OHB	Eureka	Eureka
California	LOLETA	OHB	Eureka	Eureka
California	MIRANDA	OHB	Eureka	Eureka
California	MOONSTONE BEACH	OHB	Eureka	Eureka
California	ORICK	OHB	Eureka	Eureka
California	RUTH	OHB	Eureka	Eureka
California	SCOTIA	OHB	Eureka	Eureka
California	SHELTER COVE	OHB	Eureka	Eureka
California	TRINIDAD	TRN	Eureka	Eureka
California	WEOTT	OHB	Eureka	Eureka
California	ALBION	ALB	Fort Bragg	Fort Bragg
California	ALMANOR	OMD	Fort Bragg	Fort Bragg
California	ANCHOR BAY	OMD	Fort Bragg	Fort Bragg
California	CASPAR	OMD	Fort Bragg	Fort Bragg
California	ELK	OMD	Fort Bragg	Fort Bragg
California	FORT BRAGG	BRG	Fort Bragg	Fort Bragg
California	LITTLE RIVER	OMD	Fort Bragg	Fort Bragg
California	MENDOCINO	OMD	Fort Bragg	Fort Bragg
California	POINT ARENA	ARE	Fort Bragg	Fort Bragg

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Table S1. – continued from previous page

State	Location	PCID	IOPAC Complex	Port (Current Study)
California	WESTPORT	OMD	Fort Bragg	Fort Bragg
California	BODEGA BAY	BDG	Bodega Bay	Bodega Bay/Sonoma/Marin
California	BOLINAS	BOL		Bodega Bay/Sonoma/Marin
California	DILLON BEACH	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	DRAKES BAY	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	HAMLET	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	HEALDSBURG	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	INVERNESS	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	JENNER	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	MARCONI	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	MARSHALL	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	MUIR BEACH	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	PETALUMA	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	POINT REYES	RYS	Bodega Bay	Bodega Bay/Sonoma/Marin
California	SANTA ROSA	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	SEBASTOPOL	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	STEWARTS POINT	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	TIMBER COVE	BDG	Bodega Bay	Bodega Bay/Sonoma/Marin
California	TOMALES BAY	TML	Bodega Bay	Bodega Bay/Sonoma/Marin
California	WINDSOR	OSM	Bodega Bay	Bodega Bay/Sonoma/Marin
California	ALAMEDA	ALM	San Francisco	SF Bay
California	ALAMO	OSF	San Francisco	SF Bay
California	ALVISO	OSF	San Francisco	SF Bay
California	ANTIOCH	OSF	San Francisco	SF Bay
California	BENICIA	OSF	San Francisco	SF Bay
California	BERKELEY	BKL	San Francisco	SF Bay
California	BRENTWOOD	OSF	San Francisco	SF Bay
California	CAMPBELL	OSF	San Francisco	SF Bay
California	CHINA CAMP	OSF	San Francisco	SF Bay
California	CORTE MADERA	OSM	Bodega Bay	SF Bay
California	CROCKETT	OSF	San Francisco	SF Bay
California	DALY CITY	OSF	San Francisco	SF Bay
California	DANVILLE	OSF	San Francisco	SF Bay
California	EL SOBRANTE	OSF	San Francisco	SF Bay
California	EMERYVILLE	OSF	San Francisco	SF Bay
California	FOSTER CITY	OSF	San Francisco	SF Bay
California	FREMONT	OSF	San Francisco	SF Bay
California	GLEN COVE	OSF	San Francisco	SF Bay
California	GREENBRAE	OSM	Bodega Bay	SF Bay
California	HAYWARD	OSF	San Francisco	SF Bay
California	KENTFIELD	OSM	Bodega Bay	SF Bay
California	LIVERMORE	OSF	San Francisco	SF Bay
California	LOS ALTOS	OSF	San Francisco	SF Bay
California	MARTINEZ	OSF	San Francisco	SF Bay
California	MCNEARS POINT	OSF	San Francisco	SF Bay
California	MILL VALLEY	OSM	Bodega Bay	SF Bay
California	NEWARK	OSF	San Francisco	SF Bay
California	NOVATO	OSM	Bodega Bay	SF Bay
California	OAKLAND	OAK	San Francisco	SF Bay
California	PACIFICA	OSF	San Francisco	SF Bay
California	PESCADERO	OSF	San Francisco	SF Bay
California	PINOLE	OSF	San Francisco	SF Bay
California	PITTSBURG	OSF	San Francisco	SF Bay
California	PLEASANTON	OSF	San Francisco	SF Bay
California	REDWOOD CITY	OSF	San Francisco	SF Bay
California	RICHMOND	RCH	San Francisco	SF Bay
California	RIO VISTA	OSF	San Francisco	SF Bay
California	ROCKAWAY BEACH	OSF	San Francisco	SF Bay

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Table S1. – continued from previous page

State	Location	PCID	IOPAC Complex	Port (Current Study)
California	RODEO	OSF	San Francisco	SF Bay
California	SAN FRANCISCO	SF	San Francisco	SF Bay
California	SAN FRANCISCO AREA	OSF	San Francisco	SF Bay
California	SAN JOSE	OSF	San Francisco	SF Bay
California	SAN LEANDRO	OSF	San Francisco	SF Bay
California	SAN QUENTIN	OSM	Bodega Bay	SF Bay
California	SAN RAFAEL	OSM	Bodega Bay	SF Bay
California	SAUSALITO	SLT	Bodega Bay	SF Bay
California	SOUTH SAN FRANCISCO	OSF	San Francisco	SF Bay
California	SUNNYVALE	OSF	San Francisco	SF Bay
California	TIBURON	OSM	Bodega Bay	SF Bay
California	VACAVILLE	OSF	San Francisco	SF Bay
California	VALLEJO	OSF	San Francisco	SF Bay
California	YOUNTVILLE	OSF	San Francisco	SF Bay
California	MARTINS BEACH	OSF	San Francisco	Half Moon Bay
California	MOSS BEACH	OSF	San Francisco	Half Moon Bay
California	PIGEON POINT	OSF	San Francisco	Half Moon Bay
California	POINT SAN PEDRO	OSF	San Francisco	Half Moon Bay
California	PRINCETON / HALF MOON BAY	PRN	San Francisco	Half Moon Bay
California	BIG CREEK	OCM	Monterey	Monterey Bay
California	BIG SUR	OCM	Monterey	Monterey Bay
California	CAPITOLA	OCM	Monterey	Monterey Bay
California	CARMEL	OCM	Monterey	Monterey Bay
California	FREEDOM	OCM	Monterey	Monterey Bay
California	GILROY	OCM	Monterey	Monterey Bay
California	MARINA	OCM	Monterey	Monterey Bay
California	MILL CREEK	OCM	Monterey	Monterey Bay
California	MONTEREY	MNT	Monterey	Monterey Bay
California	MOSS LANDING	MOS	Monterey	Monterey Bay
California	SALINAS	OCM	Monterey	Monterey Bay
California	SANTA CRUZ	CRZ	Monterey	Monterey Bay
California	SOQUEL	OCM	Monterey	Monterey Bay
California	WATSONVILLE	OCM	Monterey	Monterey Bay
California	WILLOW CREEK	OCM	Monterey	Monterey Bay
California	ARROYO GRANDE	OSL	Morro Bay	SLO County
California	ATASCADERO	OSL	Morro Bay	SLO County
California	AVILA	AVL	Morro Bay	SLO County
California	CAYUCOS	OSL	Morro Bay	SLO County
California	MORRO BAY	MRO	Morro Bay	SLO County
California	OCEANO	OSL	Morro Bay	SLO County
California	PASO ROBLES	OSL	Morro Bay	SLO County
California	PISMO BEACH	OSL	Morro Bay	SLO County
California	SAN LUIS OBISPO	OSL	Morro Bay	SLO County
California	SAN SIMEON	OSL	Morro Bay	SLO County
California	ALHAMBRA	OLA	Los Angeles	So Cal
California	ANAHEIM	OLA	Los Angeles	So Cal
California	AVALON	OLA	Los Angeles	So Cal
California	BALBOA	OLA	Los Angeles	So Cal
California	BLOOMINGTON	OLA	Los Angeles	So Cal
California	BONITA	OSD	San Diego	So Cal
California	CAMARILLO	OBV	Santa Barbara	So Cal
California	CARDIFF	OSD	San Diego	So Cal
California	CARPENTERIA	OBV	Santa Barbara	So Cal
California	CARSON	OLA	Los Angeles	So Cal
California	CATALINA ISLAND	OLA	Los Angeles	So Cal
California	CHATSWORTH	OLA	Los Angeles	So Cal
California	CHULA VISTA	OSD	San Diego	So Cal
California	CONCEPTION	OBV	Santa Barbara	So Cal

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Table S1. – continued from previous page

State	Location	PCID	IOPAC Complex	Port (Current Study)
California	CORONA DEL MAR	OLA	Los Angeles	So Cal
California	CORONADO	OSD	San Diego	So Cal
California	COVINA	OLA	Los Angeles	So Cal
California	DANA POINT	DNA	Los Angeles	So Cal
California	EL CAJON	OSD	San Diego	So Cal
California	EL SEGUNDO	OLA	Los Angeles	So Cal
California	FALLBROOK	OSD	San Diego	So Cal
California	GARDENA	OLA	Los Angeles	So Cal
California	GAVIOTA	OBV	Santa Barbara	So Cal
California	GLENDALE	OLA	Los Angeles	So Cal
California	GOLETA	OBV	Santa Barbara	So Cal
California	GUADALUPE	OBV	Santa Barbara	So Cal
California	HAWAIIAN GARDENS	OLA	Los Angeles	So Cal
California	HERMOSA BEACH	OLA	Los Angeles	So Cal
California	HUNTINGTON BEACH	OLA	Los Angeles	So Cal
California	IMPERIAL BEACH	OSD	San Diego	So Cal
California	IRVINE	OLA	Los Angeles	So Cal
California	LA JOLLA	OSD	San Diego	So Cal
California	LAGUNA	OLA	Los Angeles	So Cal
California	LEUCADIA	OSD	San Diego	So Cal
California	LOMPOC	OBV	Santa Barbara	So Cal
California	LONG BEACH	LGB	Los Angeles	So Cal
California	LOS ANGELES	OLA	Los Angeles	So Cal
California	LOS ANGELES AREA	OLA	Los Angeles	So Cal
California	LYNWOOD	OLA	Los Angeles	So Cal
California	MALIBU	OLA	Los Angeles	So Cal
California	MANHATTAN BEACH	OLA	Los Angeles	So Cal
California	MISSION BAY	OSD	San Diego	So Cal
California	MISSION BEACH	OSD	San Diego	So Cal
California	MISSION VIEJO	OLA	Los Angeles	So Cal
California	NATIONAL CITY	OSD	San Diego	So Cal
California	NEWHALL	OLA	Los Angeles	So Cal
California	NEWPORT BEACH	NWB	Los Angeles	So Cal
California	OCEAN BEACH	OSD	San Diego	So Cal
California	OCEAN PARK	OLA	Los Angeles	So Cal
California	OCEANSIDE	OCN	San Diego	So Cal
California	ONTARIO	OLA	Los Angeles	So Cal
California	OXNARD	OXN	Santa Barbara	So Cal
California	PACIFIC PALISADES	OLA	Los Angeles	So Cal
California	PLAYA DEL REY	OLA	Los Angeles	So Cal
California	POINT DUME	OLA	Los Angeles	So Cal
California	POINT LOMA	OSD	San Diego	So Cal
California	PORT HUENEME	HNM	Santa Barbara	So Cal
California	REDONDO BEACH	OLA	Los Angeles	So Cal
California	RESEDA	OLA	Los Angeles	So Cal
California	RIVERSIDE	OLA	Los Angeles	So Cal
California	SAN CLENENTE	OLA	Los Angeles	So Cal
California	SAN DIEGO	SD	San Diego	So Cal
California	SAN DIEGO AREA	OSD	San Diego	So Cal
California	SAN MARCOS	OSD	San Diego	So Cal
California	SAN PEDRO	SP	Los Angeles	So Cal
California	SAN YSIDRO	OSD	San Diego	So Cal
California	SANTA BARBARA	SB	Santa Barbara	So Cal
California	SANTA BARBARA AREA	OBV	Santa Barbara	So Cal
California	SANTA CRUZ ISLAND	OBV	Santa Barbara	So Cal
California	SANTA MARIA	OBV	Santa Barbara	So Cal
California	SANTA MONICA	OLA	Los Angeles	So Cal
California	SANTEE	OSD	San Diego	So Cal

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Table S1. – continued from previous page

State	Location	PCID	IOPAC Complex	Port (Current Study)
California	SEAL BEACH	OLA	Los Angeles	So Cal
California	SOLANA BEACH	OSD	San Diego	So Cal
California	SOUTH GATE	OLA	Los Angeles	So Cal
California	SPRING VALLEY	OSD	San Diego	So Cal
California	SUMMERLAND	OBV	Santa Barbara	So Cal
California	SUNSET BEACH	OLA	Los Angeles	So Cal
California	SURF	OBV	Santa Barbara	So Cal
California	TERMINAL ISLAND	TRM	Los Angeles	So Cal
California	THOUSAND OAKS	OBV	Santa Barbara	So Cal
California	VALLEY CENTER	OSD	San Diego	So Cal
California	VENICE	OLA	Los Angeles	So Cal
California	VENTURA	VEN	Santa Barbara	So Cal
California	VISTA	OSD	San Diego	So Cal
California	WESTMINISTER	OLA	Los Angeles	So Cal
California	WHITTIER	OLA	Los Angeles	So Cal
California	WILMINGTON	WLM	Los Angeles	So Cal
California	ARBUCKLE	OCA		Other CA
California	BAKERSFIELD	OCA		Other CA
California	BEAUMONT	OLA	Los Angeles	Other CA
California	BETHEL ISLAND	OCA		Other CA
California	BRODERICK	OCA		Other CA
California	BRYTE	OCA		Other CA
California	CENTERVILLE	OCA		Other CA
California	CHESTER	OCA		Other CA
California	COALINGA	OCA		Other CA
California	CORDELIA	OCA		Other CA
California	COTTONWOOD	OCA		Other CA
California	COURTLAND	OCA		Other CA
California	DIXON	OCA		Other CA
California	DOUGLAS CITY	OCA		Other CA
California	EARP	OCA		Other CA
California	ELSINORE	OLA	Los Angeles	Other CA
California	GLENN	OCA		Other CA
California	GRIDLEY	OCA		Other CA
California	IMPERIAL	OCA		Other CA
California	KERNVILLE	OCA		Other CA
California	LAKE ISABELLA	OCA		Other CA
California	LATHROP	OCA		Other CA
California	LINDSAY	OCA		Other CA
California	LOCKE	OCA		Other CA
California	LOS BANOS	OCA		Other CA
California	MCCLOUD	OCA		Other CA
California	MONO LAKE	OCA		Other CA
California	NORTH SHORE	OSD	San Diego	Other CA
California	OAKHURST	OCA		Other CA
California	PEDRO VALLEY	OCA		Other CA
California	PLACERVILLE	OCA		Other CA
California	PORTERVILLE	OCA		Other CA
California	RED BLUFF	OCA		Other CA
California	SACRAMENTO	OCA		Other CA
California	SACRAMENTO AREA	OCA		Other CA
California	SAINT HELENA	OCA		Other CA
California	SALTON SEA	OCA		Other CA
California	SNELLING	OCA		Other CA
California	SONORA	OCA		Other CA
California	STEAMBOAT SLOUGH	OCA		Other CA
California	STOCKTON	OCA		Other CA
California	TRACY	OCA		Other CA

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Table S1. – continued from previous page

State	Location	PCID	IOPAC Complex	Port (Current Study)
California	unknown or missing port	OCA		Other CA
California	VERONA	OCA		Other CA
California	VISALIA	OCA		Other CA
California	WEAVERVILLE	OCA		Other CA
California	WEED	OCA		Other CA
California	WHITEHORN	OCA		Other CA
California	WILLOWS	OCA		Other CA
Washington	OTHER OR UNKNOWN WASHINGTON PORTS	OWA		Other WA
Washington	WDF RESOURCE STATISTICS USE	OWA		Other WA

Transition Matrix Examples

Transition matrices track the movement of port between portions of the distribution of landings revenue across ports. These transition matrices are based on a five-state Markov chain model for the distribution of port share of ex vessel revenue. The five discrete states are:

1. Zero landings
2. Landings greater than 0 and less than 2.16 percent of total landings in a year
3. Landings greater than 2.16 percent and less than 5.62 percent of total landings in a year
4. Landings greater than 5.62 percent and less than 16.35 percent of total landings in a year
5. Landings greater than or equal to 16.35 percent of landings in a year (the minimum value observed in the largest port.

The lowest and highest share states (1 and 5) are qualitatively different from the other states. We discretize the remaining port share values (for all 22 years in the study period) into 3 equal sized states, with breakpoints at 0.0216, 0.0562, and 0.1635.

We then estimate a transition probability matrix (M) where the dimension of M is the number of states in the state space (5x5 in our case). We define each state as a port's presence in one of the 5 bins of the distribution of port share of groundfish ITQ landings revenue. Each cell of the matrix $M(i, j)$ contains the proportion of ports in a the i-th state in the initial time period that switch to j-th state in the next period. These values are estimates of the probability of any given port transitioning between two states, and are aptly referred to as "transition probabilities."

The five states are arranged in increasing order along the rows and columns of M (see supplemental material). So, the upper left corner shows the proportion of ports with zero landings at time t that also had zero landings at time $t+1$. Note then, that the diagonal of M represents the percentage of ports that remained in the state from t to $t+1$. High values on the diagonal of M indicate a high degree of stability in the distribution from one time period to another. High values in the off-diagonal cells of M indicated a high degree of mobility in the distribution. Put another way, no change in the distribution would produce a transition matrix that is the identity matrix. Conversely, a complete redistribution of landings revenue would produce a transition matrix with zeros on the diagonal.

Examples of calculated transition matrices are given in tables S2, S3, S4 and S5.

Table S2. Transition Matrix Converted to a Table of Frequencies for a One Year Transition Covering Implementation of ITQs

		End State (2011)				
		1	2	3	4	5
	Initial State (2010)	Zero Landings	Port Revenue Share (0, 0.0216)	Port Revenue Share (0.0216, 0.0562)	Port Revenue Share (0.0562, 0.1635)	Minimum Share of Largest Port >0.1635
1	Zero Landings	3	0	0	2	0
2	(0, 0.0216)	2	4	1	0	0
3	(0.0216, 0.0562)	0	1	1	0	0
4	(0.0562, 0.1635)	0	0	1	4	0
5	> 0.1635	0	0	0	0	1

Notes: Rows represent the initial state (2010), columns represent the end state (2011). Table S2 contains the same information as Table S3. The difference is that S2 is expressed in frequencies and S3 in proportions.

Table S3. Transition Matrix for a One Year Transition Covering Implementation of ITQs

		End State (2011)				
		1	2	3	4	5
	Initial State (2010)	Zero Landings	Port Revenue Share (0, 0.0216)	Port Revenue Share (0.0216, 0.0562)	Port Revenue Share (0.0562, 0.1635)	Minimum Share of Largest Port >0.1635
1	Zero Landings	0.60	0	0	0.4	0
2	(0, 0.0216)	0.29	0.57	0.14	0	0
3	(0.0216, 0.0562)	0	0.50	0.50	0	0
4	(0.0562, 0.1635)	0	0	0.20	0.80	
5	> 0.1635	0	0	0	0	1

Notes: matrix are proportions: the number of ports transitioning from the row state to the column state divided by totals ports in the initial state. Cells along the diagonal represent the number of ports that remained in the same state over the transition period. Table S3 contains the same information as Table S2. The difference is that S2 is expressed in frequencies and S3 in proportions.

Table S4. Transition Matrix for a Five Year Transition Covering Implementation of ITQs

		End State (2014)				
		1	2	3	4	5
	Initial State (2010)	Zero Landings	Port Revenue Share (0, 0.0216)	Port Revenue Share (0.0216, 0.0562)	Port Revenue Share (0.0562, 0.1635)	Minimum Share of Largest Port >0.1635
1	Zero Landings	2	1	0	1	0
2	(0, 0.0216)	3	1	2	0	0
3	(0.0216, 0.0562)	0	4	0	1	0
4	(0.0562, 0.1635)	0	0	0	3	0
5	> 0.1635	0	0	0	1	1

Notes: Rows represent the initial state (2009), columns represent the end state (2014). Cells of the matrix are frequencies, i.e., the number of ports transitioning from the row state to the column state. Cells along the diagonal represent the number of ports that remained in the same state over the transition period. Table S4 contains the same information as Table S5. The difference is that S4 is expressed in frequencies and S5 in proportions.

Table S5. Transition Matrix for a Five Year Transition Covering Implementation of ITQs

		End State (2014)				
		1	**2**	**3**	**4**	**5**
	Initial State (2010)	**Zero Landings**	**Port Revenue Share (0, 0.0216)**	**Port Revenue Share (0.0216, 0.0562)**	**Port Revenue Share (0.0562, 0.1635)**	**Minimum Share of Largest Port >0.1635**
1	Zero Landings	0.50	0.25	0	0.25	0
2	(0, 0.0216)	0.50	0.17	0.33	0	0
3	(0.0216, 0.0562)	0	0.80	0	0.20	0
4	(0.0562, 0.1635)	0	0	0	1	0
5	> 0.1635	0	0	0	0.50	0.50

Notes: Rows represent the initial state (2009), columns represent the end state (2014). Cells of the matrix are proportions: the number of ports transitioning from the row state to the column state divided by totals ports in the initial state. Cells along the diagonal represent the number of ports that remained in the same state over the transition period. Table S5 contains the same information as Table S4. The difference is that S4 is expressed in frequencies and S5 in proportions.

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