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ARTICLE

Catch shares drive fleet consolidation and increased targeting but not spatial effort concentration nor changes in location choice in a multispecies trawl fishery

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Abstract: Catch share systems are generally expected to increase economic rents in fisheries by increasing harvest efficiency, reducing capital costs through consolidation, and increasing the value of landed catch. However, these benefits may have costs, as consolidation and the potential for associated change in spatial distribution in landings can hinder social objectives such as maintaining access for fishery-dependent communities and small owner-operators. Achievement of such fishery management objectives are determined by changes in fisher behavior, which may be complex and difficult to predict. Predicting fisher behavior is particularly challenging in multispecies fisheries, in which the mix of species is a determinant of where and when fishing effort and landings occur. We evaluate changes in overall fishing effort, species targeting, and determinants of fishing location choice in response to catch shares in the US West Coast Groundfish Trawl Fishery. We found reductions in total fishing effort, increased targeting of some species, and no evidence of spatial effort concentration. Key determinants of location choice (distance, expected revenue, and recently fished locations) were similar among time periods, but after catch shares there was more avoidance of areas that lacked recent fishing activity or associated information with which to develop expectations of catch and bycatch. Additionally, location choice remained constant with up to 100-fold financial penalties on bycatch species.

Résumé : Il est généralement attendu des systèmes de partage de prises qu'ils accroissent les rentes dans les pêches en rehaussant l'efficacité de la récolte et la valeur des prises débarquées et en réduisant les coûts d'investissement du fait de la consolidation. Ces avantages pourraient avoir des coûts, puisque la consolidation et le potentiel de changements associés de la répartition spatiale des débarquements pourraient nuire à l'atteinte d'objectifs sociaux comme le maintien de l'accès pour les collectivités dépendant des pêches et les petits propriétaires exploitants. L'atteinte de tels objectifs de gestion des pêches est déterminée par des changements des comportements des pêcheurs, qui peuvent être complexes et difficiles à prédire. La prédiction des comportements des pêcheurs est particulièrement difficile pour les pêches multiespèces, pour lesquelles le mélange d'espèces est un déterminant du lieu et du moment de l'effort de pêche et des débarquements. Nous évaluons les changements de l'effort de pêche global, du ciblage d'espèces et des déterminants du choix du lieu de pêche en réponse au partage de prises dans la pêche aux poissons démersaux au chalut de la côte ouest des États-Unis. Nous relevons des réductions de l'effort de pêche total, un ciblage plus intense de certaines espèces et aucun indice de concentration de l'effort dans l'espace. Les déterminants clés du choix du lieu (distance, recettes prévues et lieux ayant déjà été visés par la pêche) sont semblables pour différentes périodes, mais après la mise en place du partage des prises, il y a un évitement accru de secteurs pour lesquels il n'y a pas d'activité de pêche récente ou d'information associée permettant de faire des prédictions quant aux prises et aux prises accessoires. En outre, le choix du lieu demeure constant même au vu de pénalités financières 100 fois plus grandes associées aux espèces de prises accessoires. [Traduit par la Rédaction]

Introduction

Catch share programs address the common fisheries problems of overcapitalization and the race to fish, which often ensues when fleet-wide catch quotas or season length is limited to control overexploitation. In turn, fishers have incentive to outcompete others, which typically results in increases in exploitation. Catch shares limit catch of individuals and introduce incentives to maximize the value of their individual quota. Lease or sale of individual quota can further increase efficiency by redistributing harvest and landings to more profitable vessels and areas. As a result of the incentives they create and the excess capacity that often exists when they are introduced, catch shares commonly produce several intended fishery-wide economic changes. Catch shares slow

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the rent-dissipating race to fish (Birkenbach et al. 2017), allowing fishers to time landings to fetch higher prices in the market (Scheld and Anderson 2014). Consolidation and removal of excess capacity is often a stated goal of catch share programs (Brinson and Thunberg 2016), and fleet sizes do indeed typically decrease under catch shares as quota is consolidated on fewer vessels (Branch 2009; Thunberg and Correia 2015). Some proportion of the fleet is likely to decide that they would rather sell or lease their individual quotas and focus on another fishery or line of work. Catch shares provide a mechanism for compensation as fishers exit; thus, fleet size often declines. Economic efficiency increases as fewer boats catch similar amounts of fish (Arnason 1996; Annala 1996; Grafton 1996*b*; Brinson and Thunberg 2016).

While consolidation associated with catch share implementation can increase economic efficiency, it can also conflict with social goals such as maintaining fishery access for small owner-operators and fishery-dependent communities that may depend on access to a portfolio of fisheries (Fuller et al. 2017). Fishers often become less diversified under catch shares, which can increase financial risk (Holland et al. 2017). Furthermore, individuals can be excluded from fisheries through initial allocations and redistribution of catch limits, and high individual quota prices may result in individual quotas and landings becoming consolidated in fewer communities, sometimes excluding smaller remote communities (Copes 1986; Eythórsson 2000; Himes-Cornell and Hoelting 2015; Bodwitch 2017). Given potential trade-offs between economic and social outcomes, understanding how catch shares affect the industrial structure and the spatial distribution of catch and landings is an important policy concern.

Fishers' responses to management can be unpredictable and result in unintended outcomes (Branch et al. 2006; Hilborn 2007; Fulton et al. 2010), and for multispecies fisheries, responses to catch shares may be more complex and less predictable than for single-species fisheries. The complexities arise as multispecies fisheries manage productive species along with species that are long-lived, slow-growing, and late to mature. These less productive species can experience overfishing with relatively low fishing mortality rates; thus, their effective management can require adoption of very small individual quotas that may constrain fishers' abilities to utilize individual quotas of more productive target species (Holland and Jannot 2012; Ono et al. 2013). Fishers may hoard individual quota of the constraining species if they are uncertain whether they can obtain sufficient quota to cover incidental catch of low-quota species (Holland 2016; Kuriyama et al. 2016; Pacific Fishery Management Council 2017). This may limit quota availability until the end of a season, leading to underutilization of target and nontarget species (Kuriyama et al. 2016). Catch shares provide a natural set of incentives to avoid or target particular species, especially in fisheries where discard mortality is counted against individual quotas. In effect, catch shares require fishers to consider the risks associated with bycatch prior to nets entering the water, and as a result effort should shift to areas with low expected catch rates of low-quota species (Poos et al. 2010; Batsleer et al. 2013, 2016). This shift in risk may additionally alter behavioral decisions, and understanding this response is critical for improving management performance.

We focus analysis on the US West Coast Groundfish Fishery, which transitioned from trip limits to catch shares in 2011 after a history characterized by overfishing and overcapitalization. At the transition point, catches had declined to low levels and the fishery was declared a Federal Disaster in 2000, spurring additional harvest restrictions and the disbursement of federal funds to aid fishers. A congressionally authorized vessel buyback program led to the purchase of 91 vessels (Federal Register Vol. 70, No. 133/Wednesday, July 13, 2005/Rules and Regulation), about one-third of the limited entry groundfish trawl fleet, yet overfishing continued, partly because trip limits (bimonthly cumulative limits for individual species or species groups) provided only a coarse tool to limit fishing mortality. One of the issues with trip limits was that fishers were allowed to discard fish when they hit the trip limit for that species, while continuing to fish for other species. The inevitable reductions in trip limit amounts to reduce overfishing merely had the unintended consequence of increasing discarding (as predicted by Pikitch et al. (1988)) and ultimately failed to halt overfishing of some stocks (Bellman and Heery 2013). In 2011, managers implemented catch shares as an individual fishing quota program for the bottom trawl component of the fishery and a mixture of individual fishing quotas and cooperatives for the Pacific whiting (*Merluccius productus*).

In the US West Coast Groundfish Fishery, managers implemented catch shares with the goals of increasing net economic benefits, creating individual economic stability, providing for full utilization of trawl sector allocation, all while considering environmental impacts and achieving individual accountability of catch and bycatch (Pacific Fishery Management Council and NMFS 2010). Catch shares likely increased net economic benefits for some and may have improved individual economic stability, but have not led to full utilization of catch limits in the trawl sector allocation (Kuriyama et al. 2016; Pacific Fishery Management Council 2017), although one positive benefit has been that decreases in number of tows and tow hours have reduced encounters with living habitat such as corals (Barnett et al. 2017). In addition, communities with the lowest quota allocations experienced improvements in standard of living, and communities with the highest quota allocations experienced improvements in job satisfaction (Russell et al. 2016).

Although catch shares have led to many improvements, they have also introduced a new element of risk — a defining characteristic of this multispecies fishery. Managers set quota allocations of rebuilding rockfishes at a very small proportion of target species quota, which when combined with allocations being based largely on historical catches, led to many fishers receiving very small individual quotas of some species. For example, in the first year of the individual fishing quota program, roughly 65% of participants were allocated 5 kg or less of yelloweye rockfish (*Sebastes ruberrimus*) individual quota for the entire year, which could be exceeded by capturing a single large individual (Kuriyama et al. 2016). While the quota was broadly distributed, catch of these species tends to be infrequent, uncertain, and concentrated (Holland and Jannot 2012). An unlucky tow could exhaust or exceed a fisher's individual quota for some rockfish species and force them to stop fishing unless they can find additional quota amounts on the market. Consequently, we refer to these species as "constraining" species despite the fact that their fleet-wide catches have remained below fleetwide catch limits. These constraining species have likely limited fishers' abilities to fully catch available quotas for other species (Kuriyama et al. 2016) and inhibited the effectiveness of quota markets (Holland 2016). The shifts in risk are likely to be similar to those experienced in European multispecies trawl fisheries with a discard ban (Sardà et al. 2013). Understanding the impacts of catch shares on fisher behavior can better predict outcomes and improve management to increase the likelihood of achieving a mix of economic and social objectives.

Catch shares have changed two main aspects of the fishery: fishers now have individual quotas, and discarding, which was previously allowed, is now prohibited. These changes have likely increased the risks associated with fishing, and we hypothesize that this will consolidate the fleet, concentrate fishing effort in well-known areas, increase targeting of valuable species, and make fishing location behaviors more risk-averse. Decreases in fleet size are well documented in other fisheries in the transition to catch shares, and a pre-implementation study of the US West Coast Groundfish Fishery catch share program predicted the number of vessels would decline by 50%–65% under the program (Lian et al. 2009). Under catch shares, fishers have higher individual accountability, and at-sea observers record both discards and landings on all trips, which both count against quotas. We hypothesize that overall fishing effort will decline and concentrate in specific areas of the coast with low expected bycatch probabilities. Spatial shifts towards areas with low expected catches of bycatch species have occurred in other multispecies trawl fisheries (Branch and Hilborn 2008; Poos et al. 2010; Batsleer et al. 2013, 2016), and fishers now have much stronger incentives to avoid bycatch. Fishers are commonly risk-averse (van Putten et al. 2011; Girardin et al. 2017), and we expect this risk aversion to strengthen under catch shares. Fishers will likely alter their location choices, giving more weight to prior experience and recent catches.

In this paper, we use a complementary set of approaches to investigate fisher responses in multispecies fisheries: whether and how they target or avoid particular species, and when and where they fish. We evaluate changes in targeting intensity and avoidance of particular species and evaluate changes in the magnitude and geographic distribution of effort at the individual and aggregate level. Finally, we develop a fine-scale location choice model to explore the drivers of spatial location choice behavior given complex bathymetry and associated patterns of species density distributions.

Methods

Data processing

For most of our analyses, we combined two data sources: logbook data (2007–2010) and at-sea observer data (2007–2014). Both data sources contained, for each tow, latitude, longitude, and depth that nets entered and exited the water. Catch compositions were reported for individual species, although the logbook data did not include discard amounts, while observer data did. Observers monitored roughly 20% of trips prior to 2011, after which observer coverage increased to 100% (Pacific Fishery Management Council and NMFS 2010; NMFS 2012). There was temporal overlap between the logbook and at-sea observer data for a fraction of tows from 2007 to 2010, and as a result we preferentially use data from the observer data in this period. We only prioritized records that we could match between the two data sources. Observer records likely have more precise catch records and thus were preferable to logbook records.

We categorized species as targets, constraining species, and nontarget groundfish based on the methods in Kuriyama et al. (2016). In short, target species were identified through conversations with assessment scientists and members of the seafood industry. We considered any species that was overfished and had a rebuilding plan at any point from 2007 to 2014 to be a constraining species. Nontarget groundfish were the remaining species that were designated annual total allowable catch amounts. Target species were Dover sole (*Microstomus pacificus*), lingcod (*Ophiodon elongatus*), longspine thornyhead (*Sebastolobus altivelis*), petrale sole (*Eopsetta jordani*), sablefish (*Anopoploma fimbria*), and shortspine thornyhead (*Sebastolobus alascanus*). Constraining species were bocaccio (*Sebastes paucispinis*), cowcod (*Sebastes levis*), canary rockfish (*Sebastes pinniger*), darkblotched rockfish (*Sebastes crameri*), Pacific ocean perch (*Sebastes alutus*), and yelloweye rockfish. As noted above, while catches of these species have in fact remained well below fleetwide quotas, we refer to them as constraining species because of the relatively low quotas set for them and the widespread concern that they could be constraining at the individual vessel level (Holland and Jannot 2012). Nontarget groundfish species included arrowtooth flounder (*Atheresthes stomias*), bank rockfish (*Sebastes rufus*), chilipepper rockfish (*Sebastes goodei*), English sole (*Parophrys vetulus*), greenspotted rockfish (*Sebastes chlorostictus*), greenstriped rockfish (*Sebastes elongatus*), longnose skate (*Beringraja rhina*), vermilion rockfish (*Sebastes miniatus*), widow rockfish (*Sebastes entomelas*), and yellowtail rockfish (*Sebastes flavidus*).

Changes in spatial effort

We evaluated fishery-wide changes in numbers of vessels and numbers of tows. Additionally, we evaluated port-specific changes in numbers of vessels for Astoria, Newport, Charleston, Eureka, Fort Bragg, Brookings, and Crescent City. We outline the selection and grouping of port groups later in this paper. We calculated averages for before (2007–2010) and after (2011–2014) catch shares and quantified the shift between periods.

To test the hypothesis that fishing effort declined and became increasingly concentrated, we quantified spatial autocorrelation with the Moran's *I*. We divided the coast into grid cells based on longitude and latitude (0.5° by 0.5°) and summed the number of tows in each cell in the years before (2007–2010) and after (2011–2014) catch shares. We assigned tows to cells based on the midpoint between start and end tow locations. We used the following equation:

$$(1)\qquad I = \frac{N}{W}\frac{\sum_{i}\sum_{j}\mathbf{w}_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i}(x_i - \bar{x})^2}$$

where N is the number of grid cells indexed by i longitude and j latitude; x is the number of tows per grid cell; $\bar{x}$ is the mean of x; $\mathbf{w}_{ij}$ is a matrix of spatial distances with zeroes on the diagonal; and W is the sum of all $\mathbf{w}_{ij}$ (Moran 1950). We calculated two Moran's *I* values, one for tows before and one for tows after catch shares in 2011. We used the difference in these values ($I_{\text{after}} - I_{\text{before}}$) as a test statistic, where a positive value would suggest that spatial effort has become more concentrated. To quantify statistical significance, we randomized the years associated with each tow and calculated the same test statistic with temporally shuffled tows (1000 iterations). To control for effects that may arise from changes in fleet size, we ran the analysis with tow records from all vessels and for only vessels that remained in the fishery after catch shares. Additionally, we evaluated changes in effort concentration at the port level, using only vessels that remained in the fishery after catch shares.

Changes in targeting

We used the delta plot method developed by Gillis et al. (2008) to quantify changes in targeting behavior before and after catch shares. This required computing two values for each species: the proportion of tows with zero catch and the skew of catch distribution for tows with nonzero catch. Skew was calculated from $\log_{10}$-transformed catch amounts:

$$(2)\qquad \frac{n\sum_{i=1}^{n}(x_i - \bar{x})^3}{(n - 1)(n - 2)s^3}$$

where n is the number of tows, x is the catch in tow i, and s is the standard deviation of x. The $\log_{10}$ transformations are commonly used in fisheries analysis, and thus used with this calculation (Gillis et al. 2008). For species that are targeted, we expect there to be more tows with higher catches and fewer tows with lower catches compared with a normal distribution, and thus target species will have negative skew values (left-skew distributions) and a low proportion of zero tows, while species that are avoided will have positive skew values and a high proportion of zero tows (Gillis et al. 2008). The test statistic here is the difference in skew and difference in proportion of zero tows calculated before (2007–2010) and after (2011–2014) catch share implementation. Specifically, we calculated skews after – skews before and proportion of zeroes after – proportion of zeroes before catch shares. Again, we randomized the years (1000 iterations) associated with each tow and calculated differences in skew and proportion of zero values to compare the test statistic with a null distribution.

Table 1. Example data input to random utility model based on schematic shown in Fig. 1.

Point	Date	Individual habit	Missing data	Revenue (US$)	Distance (km)	First tow	Fished tow
1	1 March 2012	1	0	400	3	1	True
1*a*	1 March 2012	0	1	0	5	1	False
1*b*	1 March 2012	1	0	100	1	1	False
2	2 March 2012	0	0	350	2	0	True
2*a*	2 March 2012	1	0	200	3	0	False
2*b*	2 March 2012	0	0	75	7	0	False

Factors that affect fishing location choices

We used random utility modeling to evaluate whether fishers changed how they chose fishing locations before and after catch share implementation. Random utility models assume that individuals have a set of options (in this case fishing locations) and will choose the option that maximizes their utility, defined here to be a linear function of distances, revenue expectations, individual habits, and fleet activity. Further details are included in the next section. Random utility models have been used to study fleet dynamics primarily in data-rich fisheries in North America, Europe, and Australia (van Putten et al. 2011; Girardin et al. 2017). Here, we apply a random utility model based on a novel point-based method of defining choice sets and expected utility associated with them. The method originated in unpublished simulation and empirical work by R. Hicks, K. Schnier, and D. Holland in 2014 (available upon request via Dan Holland; dan.holland@noaa.gov) and results in improved modeling choices in environments with fine-scale heterogeneity.

In our random utility model, choice sets characterize the range of possible specific fishing locations. Data availability and fishery characteristics can dictate the method of generating choice sets. The traditional approach is to divide the coast into discrete areas, each representing a possible fishing location (Hicks and Schnier 2008, 2010). The traditional approach can capture large-scale shifts in fishing effort but may not capture fine-scale changes that occur within discrete areas. The US west coast has locations with steep and complicated bathymetry where small changes in distance can correspond to large changes in depth, which in turn affects species composition given interspecific differences in depth distribution. We generate choice sets using a method that captures fine-scale features based on past fleet-wide fishing locations. This method takes advantage of high-resolution fisheries logbook and observer data and allows for fishing locations to be characterized by recent (e.g., within the past 30 days) and nearby (e.g., within 5 km) fishing locations. Based on the unpublished 2014 work, models with fine-scale, point-based choice sets had higher predictive abilities than models estimated using choice sets based on discrete areas. The specification of 30 days and 5 km radius had the best model fits, although we ran models with combinations of 14 days and 8 km. Inference based on coefficient signs and significances did not change with different radius values.

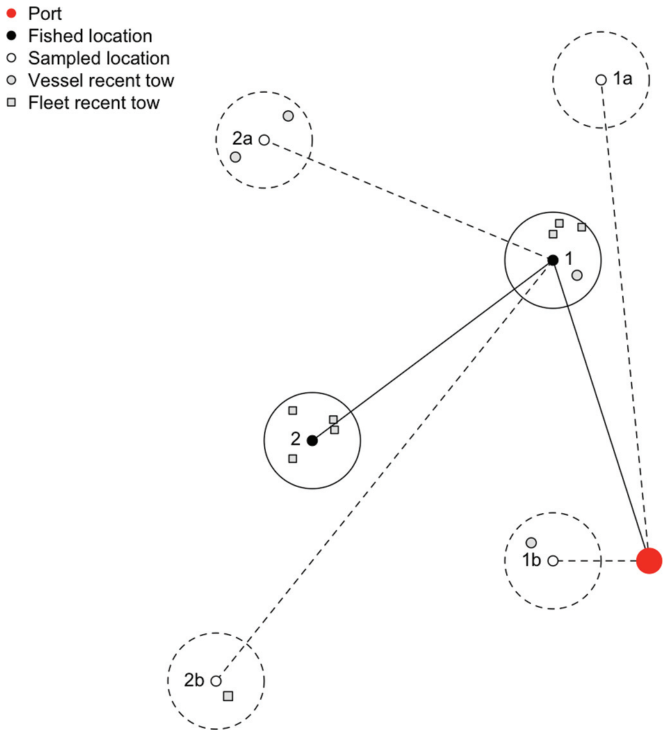


Fig. 1. The random utility model requires specification of choice sets to compare observed fishing locations with a sample of alternative possible locations. This choice set schematic shows an example choice set for Vessel A, including two empirical fished locations (solid black circles; 1 and 2) from a single trip and two sampled locations for each fished location (open circles; 1*a*, 1*b*, 2*a*, and 2*b*). Sampled locations are drawn from all tows within the fleet between 2007 and the dates for tows 1 and 2. In some cases, Vessel A fished within the spatiotemporal radius (large circles; 5 km and 30 days prior to dates for tows 1 and 2) around each location, and these values (gray circles) are used to characterize individual habit. Additionally, other vessels in the fleet fish within the spatiotemporal radius of locations, and these values (gray squares) are used to characterize missing data and revenue coefficients. The lines show distances to fished locations (solid lines) and sampled locations (dashed lines). Also shown is port location (red circle, lower right). [Colour online.]

Choice set specification

We generated choice sets by sampling 50 past tow locations for each fished tow location in the data set. Each of the sampled tow locations represented possible alternative fishing locations drawn for a set of all observed fishing locations chosen by the port group. To have sufficient fishing history, we used 2009 as the first year of analysis allowing locations to be sampled from 2007 and 2008. We generated choice sets separately for the top six ports in the fishery: Astoria, Oregon; Newport, Oregon; Charleston, Oregon; Brookings, Oregon, and Crescent City, California, combined; Eureka, California; and Fort Bragg, California. These six port groups account for 75% of the total landings in the fishery. Vessels were assigned to port groups based on the vessel's most common port of return. Tow locations were sampled in proportion to the effort observed by depth intervals. Each tow was assigned to a depth bin based on the average recorded depth between start and end tow locations. Depth bins were originally in 50 fathom increments (1 fathom = 1.829 m), but we report them in metres (0–91, 91–183, 183–274, 274–366, 366–549, 549–914, and 914–1280 m).

Choice sets require specification of characteristics (like distance, expected revenues, and habits) for all of the alternative locations — the one chosen as well as the sample of previous alternative locations. We describe the choice set specification process with a schematic (Fig. 1) and show example data (Table 1) used in the random utility model. In the schematic, tow 1 occurred on

1 May 2012, and tow 2 occurred on 2 May 2012 for Vessel A. Both tows were consecutive in a single fishing trip, and two alternative locations were sampled for each fished tow. Location samples were drawn from prior fished tows, in this case tows that occurred between 1 January 2007 (i.e., point 1*a* in Fig. 1) and 1 or 2 May 2012 (e.g., point 1*b* in Fig. 1), from all vessels in the fleet. The spatiotemporal radius characterizes the recent fleet activity, defined to be 5 km and 30 days prior to the tow date. Note that the sampled locations associated with each fished tow can be from a wide time period (roughly 5 years in this example), and the radius is applied to both fished and sampled locations. We also explored using a larger radius but model fits degraded. All fished tows that occurred within the spatiotemporal radius (e.g., within 5 km of the location and between 1 April and 1 May 2012) are indicated by gray symbols. Individual habit variables had a value of 1 if Vessel A fished within the spatiotemporal radius within the past 30 days (gray circles in Fig. 1). Missing data variables, in contrast, take a value of 1 if no vessels fished within the spatiotemporal radius in the past 30 days, and thus there are no data to construct revenue expectations (gray squares in Fig. 1). A negative coefficient on the missing data variable therefore demonstrates avoidance of areas not recently fished by the fleet. Similarly, the expected revenue variable is calculated from tows that occurred within the spatiotemporal radius. Distances for the first tow were based on the distance from port (unlabeled red point in Fig. 1, lower right side), while for later tows this is the distance from the previous tow. Additional variables in the random utility model data specify whether the tow was the first of a trip and if a tow was fished or sampled, allowing us to estimate separate coefficients for the first versus later tows. Thus, the set of predictor variables is individual habit, missing data, revenue, distance, and dummy variables for first tow or later tow.

We considered the three primary factors in location choices to be revenues, distances, and habits. Net revenues for catch in each tow were calculated with the following equation:

$$r_{\mathrm{net}} = r - c \tag{3}$$

where r_{net} is net revenue, r is the total revenue summed across species, and c is the quota costs summed across species. We calculated revenues as the monthly ex-vessel prices for species at each port without any time lags. The benefit of these price data is that they capture temporal market conditions. For annual quota pound prices (equivalent to quota share lease prices), we used the species-specific 4-year average quota costs presented in Holland (2016). Tows that occurred prior to 2011 had no quota costs, as catch shares were not in place, and the net revenue values were equal to total revenue.

We calculated distances for first tows in each trip as the distance from port to start location and distance for later tows on each trip as the distance from the previous tow's end location to the prospective tow's start location. We used the spherical law of cosines (great circle distance) for calculating distances in kilometres. Expected revenues (REV) were calculated with an arithmetic mean of revenue per tow for all tows within the spatiotemporal radius. Missing data (Dmiss) variables were 1 if there were no records within the spatiotemporal radius and 0 if there were. Individual habit variables (Dhab) had a value of 1 if an individual vessel had records within the spatiotemporal radius and a value of 0 if not. Prior year individual habit variable (Dhab_1) were handled the same way, except that the temporal filter was the past 30 days of the previous year. Fishers may have a tendency to return to the same locations at particular times of year, and we quantify this tendency with inclusion of this prior year coefficient. There also is a variable indicating whether the empirical tow is the first ($D_0 = 1$) or later ($D_1 = 1$) tow of a trip. Here, distance was a proxy for fuel and labor costs, as both are expected to increase linearly as boats travel further from port.

All of this information was incorporated into a linear expected utility function and estimated with a standard conditional logit model:

$$\begin{aligned} V_{ijt} = {} & \beta_{\mathrm{dist1}} D_1 \mathrm{DIST}_{ijt} + \beta_{\mathrm{dist0}} D_0 \mathrm{DIST}_{ijt} + \beta_{\mathrm{rev1}} D_1 \mathrm{REV}_{ijt} \\ & + \beta_{\mathrm{rev0}} D_0 \mathrm{REV}_{ijt} + \beta_{\mathrm{miss}} \mathrm{Dmiss}_{ijt} + \beta_{\mathrm{hab}} \mathrm{Dhab}_{ijt} + \beta_{\mathrm{hab1}} \mathrm{Dhab}_{1\_ijt} + \varepsilon_{ijt} \end{aligned} \tag{4}$$

where V_{ijt} is utility for individual i at location j in time period t, and ε_{ijt} are the factors that affect location choices and are unaccounted for explicitly with variables.

Target and constraining species quotas can differ by orders of magnitude, and the consequences of exceeding individual quotas for constraining species can be high even if the probability is low. Thus, net revenue calculations that deduct quota costs may not fully account for the risk that fishers perceive. Risk may have many components: the risk of exceeding individual quotas, the risk that additional quota for specific species might not be available on the quota market, and the risk that an individual will be unable to fish. To account for these higher perceived risks associated with obtaining quota for constraining species, we ran models with net revenue calculated using quota prices for constraining species assumed to be 5, 10, 50, and 100 times actual prices. Under these scenarios, areas associated with constraining species can have low or even negative expected revenue values. If these models with higher quota cost multipliers had improved model fits, this would provide some indirect evidence for risk avoidance.

Performance metrics

We quantify parameter precision with confidence intervals for each port by year. For the distance to revenue ratios, we calculated parameter ratio precision using the Krinsky–Robb method (Krinsky and Robb 1986). We identified significant changes both year to year and in response to catch shares from these confidence intervals.

We quantified model fits with two predictive metrics and one distance-based metric. The predictive metrics were based on the calculated probabilities of each choice (the location actually chosen and 49 randomly sampled tows) in the choice set. The "correct tow" metric, calculated for each choice, is the proportion of choices in which the location actually chosen also had the highest estimated probability of being chosen. The "correct area" metric is the proportion of choices in which the locations with the highest estimated choice probability was within 5 km of the location actually chosen. The distance metric is the average distances between the location with the highest estimated choice probability and the location actually chosen.

Analyses were conducted in the statistical programming language R (R Core Team 2017). The packages "dplyr" (Wickham et al. 2017), "lubridate" (Grolemund and Wickham 2011), "doParallel" (Revolution Analytics and Weston 2015), and "mlogit" (Croissant 2013) were essential for data processing and model fitting.

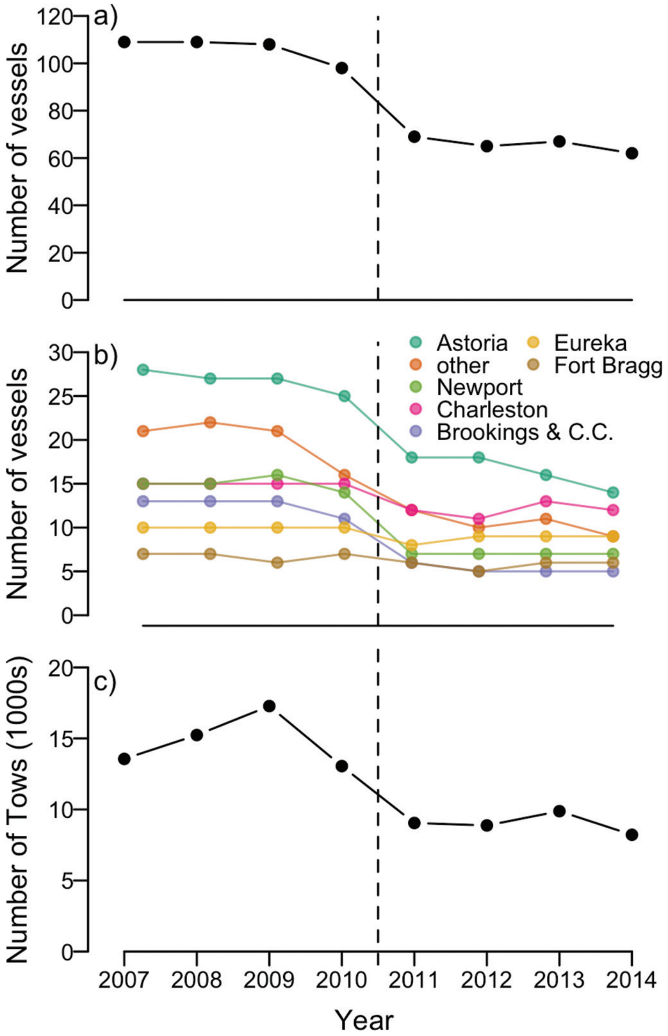
Results

Changes in spatial effort

After catch shares, the fleet consolidated and fishing effort generally declined throughout the region. The number of vessels declined 38% from a mean of 106 vessels before to a mean of 66 vessels after catch shares (Fig. 2*a*). Newport and Astoria had declines in average fleet size of 53% and 38%, respectively (Fig. 2*b*). Declines in the "other" group occurred in Bellingham Bay, San Francisco, Half Moon Bay, and Westport. The mean number of tows declined by about 39% from 14 783 in 2007–2010 to 9005 in 2011–2014 (Fig. 2*c*).

Contrary to our expectations, there was no evidence that fishing became more spatially concentrated across the entire fishery after catch shares. For tows from all vessels, the opposite effect

Fig. 2. Trends in the total number of vessels (*a*), number of vessels in each port-associated fleet (*b*), and total number of tows (*c*) for 2007–2014. The dashed vertical line divides the years prior to (2007–2010) and after (2011–2014) catch share implementation. [Colour online.]



was found, with spatial autocorrelation actually declining significantly (difference in Moran's I values of −0.018, $p < 0.05$) indicating that effort was less patchily distributed. For tows from only the vessels remaining in the fishery after catch shares, there was no significant change in spatial autocorrelation (difference in Moran's I of 0.003, $p = 0.62$).

There was no evidence of spatial concentration at the port level for vessels that remained in the fishery after catch shares. Newport (difference in Moran's I of −0.065), Charleston (−0.045), Eureka (−0.040), and Brookings and Crescent City (−0.118) all had statistically significant declines in Moran's I values, suggesting that the footprint of spatial fishing effort expanded after catch shares. Astoria and Fort Bragg had statistically insignificant changes in Moran's I.

Changes in targeting

Delta plots showed increased targeting after individual transferable quotass as evidenced by 14 of 23 species having significant decreases in skew values (Fig. 3). Increased targeting was most notable among target species; five of six target species had decreases in skew values and were caught in more than 50% of tows before and after catch shares (Figs. 3*a*–3*b*). The biggest targeting increases were for Dover sole, thornyheads, and sablefish (the "DTS" complex), which are typically targeted together, and there was also increased targeting of some constraining rockfish species.

Factors that affect fishing location choices

Location choice before catch shares (2009–2010) was largely similar to location choice after catch shares (2011–2014); coefficients for distance, revenue, and individual habitat were significant with consistent signs throughout 2009–2014 (Table 2; Fig. 4). Fishers generally fished in locations relatively close to their home port on the first tow of a trip and closer to their previous tow location for subsequent tows. Evidence for this behavior is that coefficients for first-tow distance were always negative and were significant in 30 out of 36 port–year combinations in 2008–2014 (Table 2; Fig. 4). Similarly, the coefficients for later tow distance were significant and negative in all years and all ports (Table 2; Fig. 4). These negative distance coefficients indicate that longer distances resulted in lower utility values, which is reasonable as distance is a strong proxy for costs of fuel and the lost opportunity costs of time spent steaming instead of fishing. Distance coefficients for first tows are smaller than that for later tows, indicating that vessels are willing to steam further for the first tow than from one tow to the next.

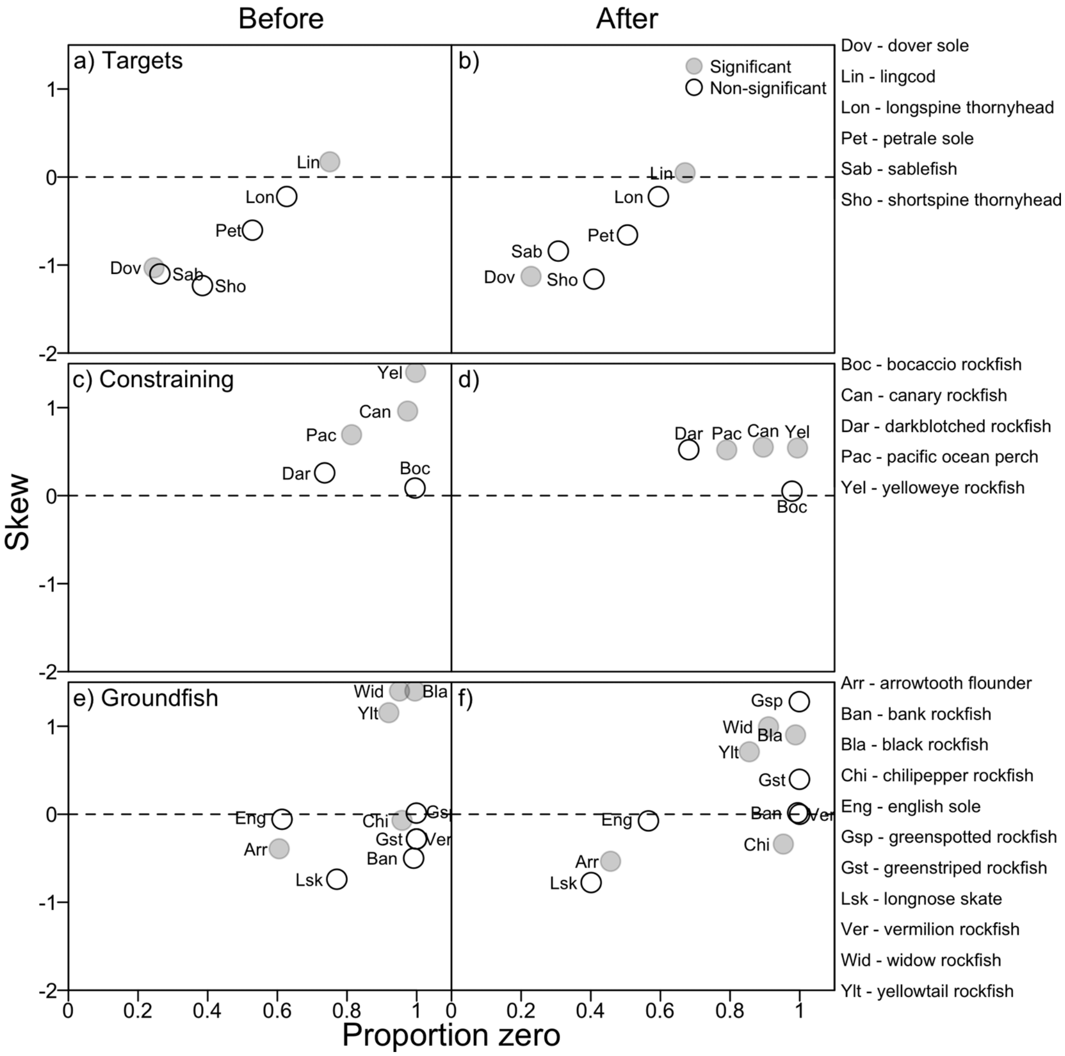
Fishers generally fished in locations with higher expected revenues. Coefficients for first tow revenue and later tow revenue were always positive and were significant in most ports in most years (Table 2; Fig. 5). Individual habit strongly influenced fishers' location choices; they tended to fish in the same locations that they had fished in the previous 30 days of the tow date and in the corresponding 30-day period from the previous year, as evidenced by positive and significant coefficients for individual habits in all years and all ports (Table 2; Fig. 5). Positive revenue coefficients indicate that higher revenues resulted in higher expected utilities.

Only Astoria, Newport, and Eureka showed evidence of significantly different fishing behaviors after catch shares. Astoria had the most consistent shift in distance to revenue ratios for later tows (Fig. 6*a*). The more negative ratios after catch shares suggest that fishers were less willing to travel long distances after the first tow. Newport and Eureka had significant shifts from 2010 to 2011 (Figs. 6*b* and 6*e*). In Newport, 2010 seems to be a distinct year (Fig. 6*b*), whereas in Eureka, 2011 and 2014 had distinct distance to revenue trade-offs (Fig. 6*e*). Note that the scale of revenue parameters was extremely small, resulting in very large uncertainties for some year–port combinations (e.g., Fig. 6*c* — Charleston 2013).

Positive coefficients for the variable for no observed tows (missing tows; D_{miss}) from which to calculate expected revenue suggest that fishers in the two largest ports, Astoria and Newport, shifted location choice after catch shares. In 2010, the year before catch shares, all these D_{miss} coefficients were positive and significant, indicating that individual fishers were willing to fish in locations that the fleet had not fished in the past 30 days (Table 2). After catch shares in 2011, Astoria D_{miss} coefficients were negative and significant in 2011 and 2013–2014 (Table 2), and Newport D_{miss} coefficients were not significant, negative in 2011 and 2014, and positive in 2012 and 2013 (Table 2). In the other ports, coefficients were mostly positive and significant, suggesting that behavior remained consistent after catch shares (Table 2). Sensitivity tests on these results showed that coefficient significance was consistent when model runs were performed with a broader spatial radius of 8 km instead of 5 km and narrower temporal window using information from the prior 14 days instead of 30 days. So while a spatiotemporal radius of 5 km and 30 days had the best fit, inference based on model results was similar with different configurations.

Predictive ability at the port level was highest for Astoria and lowest for Brookings and Crescent City. On average, models accu-

Fig. 3. Delta plots from observer data showing the relation between proportion of tows with zero fish and the skewness of the distribution of log$_{10}$ catch amounts for target species (*a*–*b*), constraining species (*c*–*d*), and other groundfish (*e*–*f*). A skew above zero indicates species with fewer large catches than expected, while a skew below zero indicates more large catches than expected. The left column is years before catch shares (2007–2010), and the right column is years after catch shares (2011–2014). Gray shading indicates species with significant ($p < 0.05$) decreases in skew values after catch shares were implemented. No species had significant increases in skew or significant increases or decreases in the proportion of tows with zero values.



rately predicted 42% of tows and 48% of areas for Astoria, while for Brookings and Crescent City, models predicted a mean of 18% of tows and 27% of areas (Table 3).

Contrary to our expectation, models that calculated expected revenue using inflated quota prices for constraining species did not improve model performance. Increasing quota prices by factors of 5, 10, 50, and 100 decreased significance in the first and later tow revenue coefficients across ports and years (refer to online Supplemental Material[1], Tables S1–S4). Additionally, predictive metrics were nearly identical across ports, years, and quota price multipliers (Supplemental Material[1], Tables S5–S8). This empirical result is consistent with a previous ecosystem simulation model of the US West Coast Groundfish Fishery that found that increasing quota prices to $\$50\cdot\text{kg}^{-1}$ did not noticeably impact fleet dynamics because expected catch of the constraining species was still very low, making expected quota cost low as well (Kaplan et al. 2014).

Discussion

Catch shares did not result in concentration of spatial effort, strong avoidance, nor drastic shifts in location choice in the US West Coast Groundfish Fishery. There may have been more evidence of change if the fishery had transitioned from open access or more derby-like management to catch shares, but overall many of the characteristics we evaluated remained constant. Notably, the model fit for the location choice model was not improved by assuming higher quota costs for constraining species as a proxy for risk. This result may suggest that fishers accounted for bycatch risk in the years before and after catch shares.

Fishing effort and fleet size declined after catch shares were implemented in the US West Coast Groundfish Fishery, which is consistent with responses to catch share policies in Canada (Crowley and Palsson 1992; Grafton 1995), New Zealand (Grafton 1996*b*), and Alaska, USA (Abbott et al. 2010). Nearly all the ports

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[1] Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfas-2019-0005.

Table 2. Table of random utility model coefficients.

Fleet	Coefficient	2009	2010	2011	2012	2013	2014
Astoria	First tow distance	−0.009***	−0.010***	−0.006***	−0.004***	−0.002*	0.000*
	Later tow distance	−0.045***	−0.054***	−0.064***	−0.059***	−0.058***	−0.057***
	First tow revenue	0.033***	0.026***	0.019***	0.027***	0.016***	0.011*
	Later tow revenue	0.020***	0.015***	0.011***	0.009***	0.011***	0.009***
	Missing data	0.294***	0.358***	−0.147	−0.225*	−0.207*	−0.211*
	Individual habit	2.094***	2.093***	2.059***	2.200***	2.051***	2.447***
	Individual habit last year	0.119*	0.450***	0.230***	0.275***	0.530***	0.433***
Newport	First tow distance	−0.019***	−0.006*	−0.011	−0.005	−0.005	−0.029***
	Later tow distance	−0.054***	−0.049***	−0.060***	−0.052***	−0.054***	−0.052***
	First tow revenue	0.012***	0.024***	0.023***	0.002	0.017***	0.016***
	Later tow revenue	0.008***	0.020***	0.007	0.006	0.009***	0.005*
	Missing data	0.192*	0.583***	0.032	0.096	0.124	−0.126
	Individual habit	1.647***	1.693***	1.574***	1.507***	1.224***	1.111***
	Individual habit last year	0.249*	0.195*	0.427*	0.510*	0.346*	0.223
Charleston	First tow distance	−0.008*	−0.004	−0.014*	−0.021***	−0.003	−0.014*
	Later tow distance	−0.054***	−0.048***	−0.052***	−0.044***	−0.048***	−0.046***
	First tow revenue	0.009*	0.015***	0.017***	0.016***	0.017***	0.010*
	Later tow revenue	0.005*	0.009***	0.009***	0.005	0.000	0.005
	Missing data	0.200	0.739***	0.507***	0.388*	0.153	−0.178
	Individual habit	1.912***	2.251***	2.169***	2.201***	2.081***	1.790***
	Individual habit last year	0.261***	0.662***	0.348***	0.645***	0.790***	0.732***
Brookings and Crescent City	First tow distance	−0.011***	−0.014***	−0.028***	−0.013*	−0.015*	−0.029***
	Later tow distance	−0.037***	−0.035***	−0.039***	−0.028***	−0.028***	−0.036***
	First tow revenue	0.010*	0.009*	0.013***	0.014*	0.020***	0.005
	Later tow revenue	0.009***	0.008*	0.014***	0.021***	0.017***	0.007***
	Missing data	0.460*	0.451*	0.302	0.506	1.020***	0.727*
	Individual habit	1.307***	1.574***	1.252***	1.538***	1.883***	2.017***
	Individual habit last year	0.197	0.370***	0.074	−0.124	0.178	0.355*
Eureka	First tow distance	−0.007*	−0.013***	−0.012***	−0.019***	−0.013***	−0.012***
	Later tow distance	−0.056***	−0.054***	−0.052***	−0.051***	−0.047***	−0.058***
	First tow revenue	0.023***	0.027***	0.016***	0.018***	0.014***	0.009*
	Later tow revenue	0.023***	0.023***	0.011***	0.018***	0.021***	0.014***
	Missing data	0.950***	1.199***	0.574***	0.867***	1.004***	0.957***
	Individual habit	2.011***	2.082***	2.070***	1.933***	2.548***	2.438***
	Individual habit last year	0.256*	0.239*	0.291*	0.333*	0.142	0.376***
Fort Bragg	First tow distance	−0.017***	−0.010***	−0.011*	−0.016***	−0.006*	−0.015***
	Later tow distance	−0.045***	−0.045***	−0.052***	−0.050***	−0.053***	−0.056***
	First tow revenue	0.027***	0.016*	0.009*	0.014*	0.025***	0.003
	Later tow revenue	0.012***	0.011***	0.005*	0.007*	0.011***	0.004*
	Missing data	0.197	0.338*	0.198	0.221	0.799***	−0.063
	Individual habit	1.011***	1.137***	1.711***	1.635***	1.968***	1.441***
	Individual habit last year	0.189*	−0.075	0.309*	0.307*	0.418***	0.403***

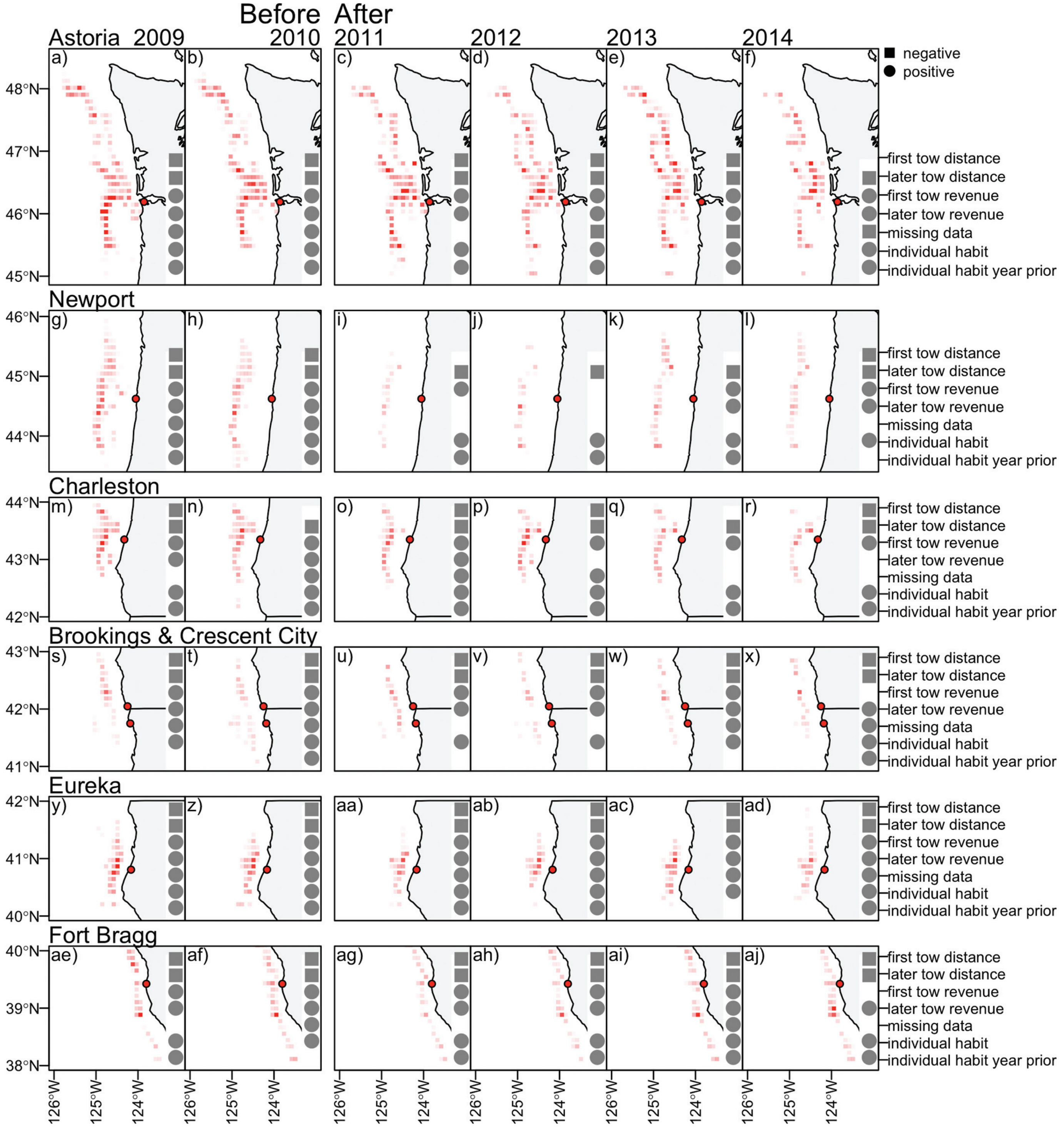
Note: Coefficients were significant with *p* values less than 0.05 (*) and 0.001 (***).

experienced declines in fleet size, and Astoria and Newport experienced the largest declines in terms of numbers of vessels. Some smaller ports maintained comparatively little change in fleet sizes. In all these cases, the theory of catch shares accurately predicts that fleet sizes and effort will decline as fishers consider their opportunity costs and decide to exit the fishery (Grafton 1996*a*). However, some design aspects of catch share programs may limit the magnitude of declines. Managers in the US Northeast, for example, gave fishers the option to volunteer to join a catch share program or remain in open access. About half of the permits joined the catch shares program, but fishers were allowed to move between catch shares and open access. In this case, the number of permits did not decline, although in the sectors, catches consolidated on fewer vessels (Holland et al. 2013).

We found that effort in the US West Coast Groundfish Fishery did not concentrate after catch shares, suggesting that fishers adopted different behavioral strategies to increase their targeting abilities. There is evidence of behavioral adjustments like fishing at different times of day, with different gear, and with shorter tows in this fishery (Miller and Deacon 2017). These adjustments likely explain the increase in targeting without evidence of spatial effort concentration. Shifts in fishing effort are often responses to concomitant factors like changes in local fish abundance (Ames 2004; Morato et al. 2006), gear bans (Bellman et al. 2005), local bycatch events (Dunn et al. 2014; Abbott et al. 2015), spatial closures (Hutton et al. 2004), or even religious events (Poos and Rijnsdorp 2007). Fishers are highly adaptable, and behavioral adjustments such as altering fishing times or changing gear are seen after catch share implementation in fisheries in Alaska (Abbott et al. 2015), southeast Australia (Baelde 2001), and the North Sea (Mortensen et al. 2018).

We found evidence of increased targeting of the high-value species after catch shares, particularly for the DTS complex after catch shares were implemented. Surprisingly we also found moderate evidence of increased targeting for some constraining rockfish species, which may be due to a combination of their increasing biomass and overlap in their distribution with target species on the outer continental shelf and upper slope. Darkblotched rockfish and Pacific ocean perch, for which our results suggested increased targeting, may be taken incidentally while targeting the DTS complex. However, these species were not found to be associated at the finer spatial scales sampled by scien-

Fig. 4. Number of tows in each 10 km × 10 km grid cell for vessels in each port group (rows) and year (columns). Significance and signs for coefficients are shown in the right of each panel. Nonsignificance (no point) and significance (solid; $p < 0.05$) are shown for positive (circle) and negative (square) coefficients. Each grid shown is filtered to contain at least three tows from at least three vessels. [Colour online.]



tific trawl surveys (Thorson and Barnett 2017). Despite this, total catches for all constraining rockfishes remained well below total quotas (Kuriyama et al. 2016). For constraining species, average catch rates and the frequency of large catches in a single tow did decline after implementation of catch shares (Pacific Fishery Management Council 2017). Thus, fishers may have been successful at avoiding dense concentrations of these species, but frequent incidental catch may be unavoidable due to some similarity in depth and latitudinal distribution with target species. Our results also find increased targeting of widow rockfish. Widow rockfish was a potentially constraining species at one time, but has since been rebuilt, and quotas were dramatically increased soon after implementation of catch shares. Avoidance would no longer have been a concern, and some fishers began targeting widow rockfish with midwater trawl gear (though this analysis was restricted to bottom trawl gear). Considering all evidence, catch shares have

Fig. 5. Estimates for each coefficient through time. Estimates (points) with 95% confidence intervals (tails) are arranged by port (colour). Significant values ($p < 0.05$) are indicated with solid points, while nonsignificant values have open points. Vertical dashed gray lines indicate the year of catch share implementation (2011), and horizontal dashed gray lines indicate zero values. If viewing in grayscale, points for each year are slightly offset for each year (Astoria furthest left, Fort Bragg furthest right). [Colour online.]

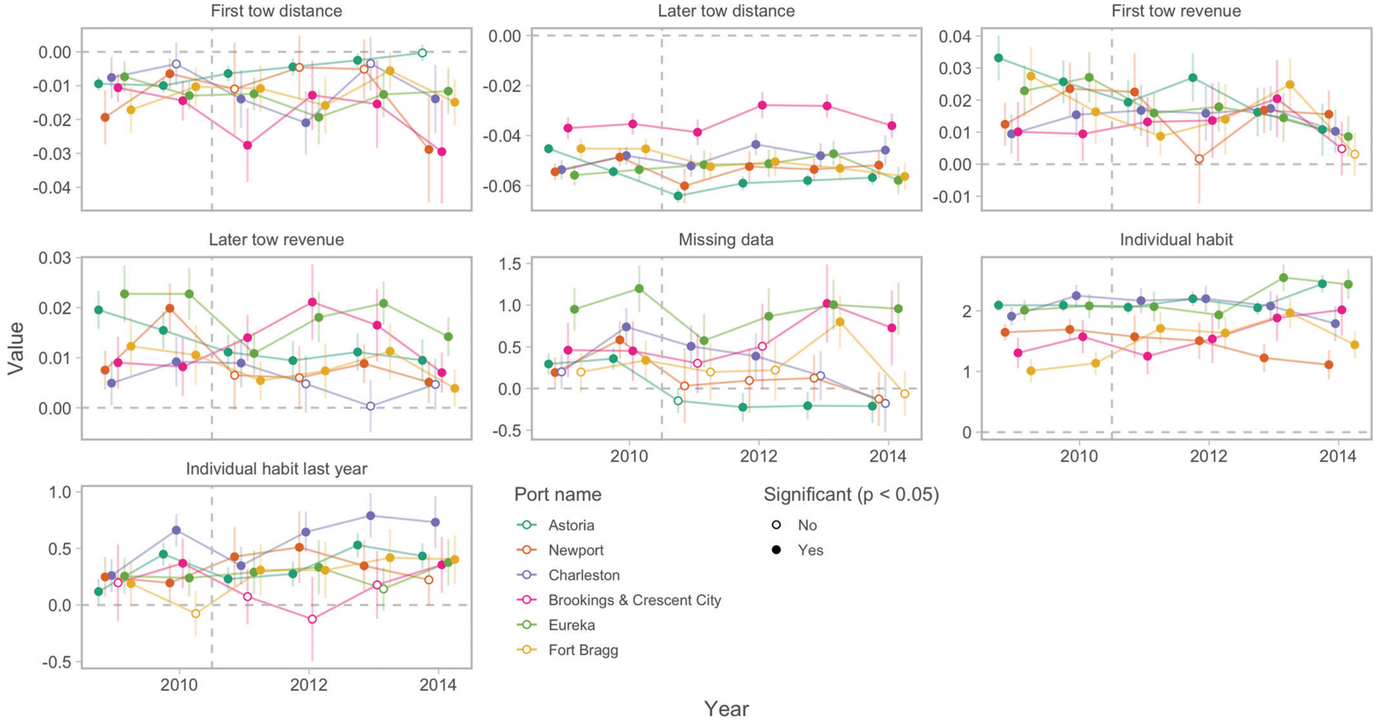


Fig. 6. Ratios of distance to expected revenue coefficients for first tow (circles) and later tows (triangles) before and after catch shares (implemented in 2011; gray vertical line) with 95% confidence intervals (tails). More negative ratios suggest fishers are less willing to travel further from their port or previous tow location, and there is no consistent trend among year and fleet.

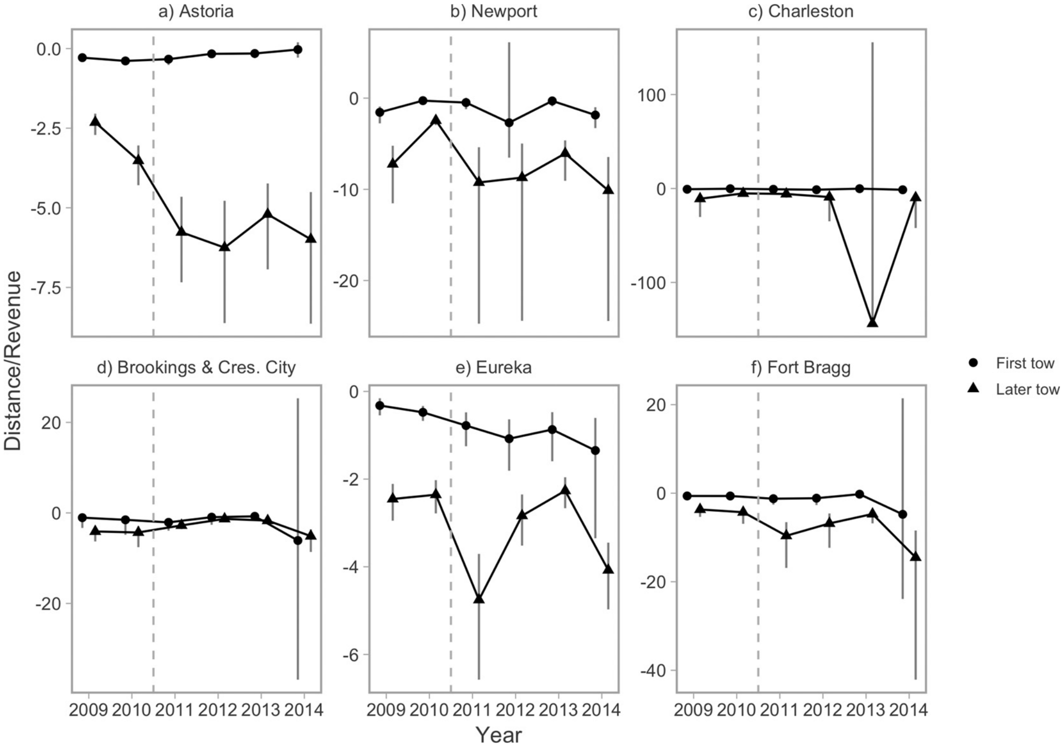


Table 3. Predictive metrics by port and year.

Port	2009	2010	2011	2012	2013	2014
Correct tow (%)						
Astoria	38	39	43	43	41	46
Newport	24	23	26	19	21	19
Charleston	26	27	24	19	21	18
Brookings and Crescent City	20	21	18	17	16	18
Eureka	21	21	25	21	23	25
Fort Bragg	14	15	24	26	23	21
Correct area (%)						
Astoria	39	40	44	56	53	57
Newport	29	24	28	39	36	38
Charleston	33	29	26	38	42	44
Brookings and Crescent City	27	23	20	29	31	32
Eureka	29	25	29	41	40	44
Fort Bragg	22	18	25	44	41	39
Distance (km)						
Astoria	84	78	65	16	17	15
Newport	56	78	61	20	19	19
Charleston	32	45	45	17	17	16
Brookings and Crescent City	129	163	134	27	26	23
Eureka	36	62	58	17	16	15
Fort Bragg	52	67	62	19	19	19

Note: Correct tow is the percentage of correctly predicted tows, correct area is the percentage of correctly predicted areas, and distance is the distance between predicted and empirical tows.

led to increased targeting efficiency while having mixed influence on avoidance; thus, it does not appear that the risk of incidental catch of constraining species is a primary driver of fisher behavior.

Multispecies catch share fisheries are complex, and policies will likely need to be adapted to improve ecological, social, and economic outcomes. Risk pools are one example of adaptation in the US West Coast Groundfish Fishery. Many fishers joined risk pools to ameliorate the risk of exceeding quotas of constraining species. Members of the risk pools share their quota and coordinate fishing effort to minimize chances that catches are limited by constraining species. Risk pools may have facilitated avoidance and higher utilization of target species (Kauer et al. 2018). Fishers that joined risk pools have greater access to quota to cover incidental catch of constraining species, but they also agreed to abide by contractually binding rules intended to reduce risk of large catches of these species (Holland and Jannot 2012). Additional innovations may include consideration of multispecies interactions when setting total allowable catches (Ulrich et al. 2011), allowing species conversions (Woods et al. 2015*a*, 2015*b*, 2016), and identification of spatiotemporal species complexes (Dolder et al. 2018).

Consistent with previous analyses, we found that fishers tend to fish in areas that (*i*) they have fished before, (*ii*) have higher expected revenues, and (*iii*) are closer to previous tow or port locations to reduce steam time and associated cost. Previous random utility models also found choice probabilities increased with higher expected revenue and decreased with distance (Holland and Sutinen 2000; Haynie et al. 2009; Abbott and Wilen 2011), and habit is a significant predictor in roughly 75% of reviewed fleet dynamics studies (Girardin et al. 2017). The relative importance of revenue and distance in determining location choice remained relatively constant before and after catch shares for most fleets.

Given that our fleetwide spatial analysis indicated a relative increase of effort closer to shore with catch shares, we might have expected to see the ratio of the absolute value of the distance over expected revenue coefficients to increase, indicating a stronger reluctance to travel further. However, we did not see consistent changes in this ratio after catch shares, indicating that the change in spatial effort was more likely caused by changes in spatial distribution of quota or changes in habit rather than short-term profit considerations of individual fishers.

Before catch shares, fishers were likely to fish in areas without recent activity as evidenced by positive and significant missing data (D_{miss}) variables. Negative and insignificant parameters for the missing data variables after catch shares for some fleets suggest fishers for these fleets were more likely to avoid areas not recently fished relative to before catch shares. However, results varied by fleet and year. Fishers in Astoria tended to avoid areas not recently fished, whereas fishers in Brookings, Crescent City, and Eureka were still more likely to fish in areas where others had not recently fished. This difference may be related to the spatial extent of fishing grounds. Larger ports like Astoria and Newport have large spatial footprints of fishing effort, whereas smaller ports like Brookings and Crescent City may have better defined fishing grounds. Skippers in the larger ports may be less familiar with the broad fishing grounds and rely on recent catch information gathered from others.

Fishers in the US West Coast Groundfish Fishery may not account for incidental catch of constraining species on monetary terms. Model performance was essentially unchanged when increasing quota costs up to 100-fold. Rebuilding plans in the US West Coast Groundfish Fishery have been in place since 2000, and fishers may have adopted strategies to avoid constraining species in the years prior to the study period. Fishers appear to have sufficiently avoided these species as catch rates and large catch incidents for constraining rockfish species declined after catch shares. With landings well below catch limits and a series of years with good conditions for recruitment, stocks of nearly all of the constraining species have been rebuilt.

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