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Bycatch Quotas, Risk Pools, and Cooperation in the Pacific Whiting Fishery

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The United States Pacific whiting fishery uses mid-water trawl gear to target Pacific whiting off the United States West Coast. The fishery is subject to sector-specific bycatch caps for Chinook salmon (*Oncorhynchus tshawytscha*) and several rockfish species (widow rockfish–*Sebastes entomelas*, canary rockfish-*Sebastes pinniger*, darkblotched rockfish–*Sebastes crameri*, Pacific Ocean Perch (POP)-*Sebastes alutus*, and yelloweye rockfish-*Sebastes ruberrimus*). Chinook bycatch can include fish from endangered populations and rockfish stocks were recovering from severe depletion though most are now rebuilt. Catch of these species is rare and uncertain, making it difficult for vessels to meet strict individual performance standards. Consequently the industry has developed risk pools in which bycatch quota for a group of vessels is pooled, but vessels are required to follow practices that minimize bycatch risk including temporal and spatial fishing restrictions. The risk pools also require vessels to share information about bycatch hotspots enabling a cooperative approach to avoid bycatch based on real-time information. In this article we discuss the formation and structure of these risk pools, the bycatch reduction strategies they apply, and outcomes in the fishery in terms of observed bycatch avoidance behavior and utilization of target species. The analysis demonstrates the ability of these fishers to keep bycatch within aggregate limits and keep individual vessels from being tied up due to quota overages.

Keywords: bycatch, fisheries, trawl, risk pools, Pacific whiting, individual bycatch quotas

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INTRODUCTION

Fishing gear, particularly trawl gear, often has limited selectivity and captures fish or marine fauna that are not the target of the fishery. United States law mandates that "conservation and management measures shall, to the extent practicable, (a) minimize bycatch and (b) to the extent bycatch cannot be avoided, minimize the mortality of such bycatch." This, along with strict legal requirements to eliminate overfishing and rebuild overfished stocks, has put increasing pressure on fishery managers and the industry to reduce bycatch. Fishery managers and industry also face pressure from interest groups. NGOs have successfully harnessed consumer pressure to incentivize bycatch reduction, most famously with the development of the dolphin-safe label for tuna, which led to global changes in tuna fishing methods to reduce dolphin bycatch (Teisl et al., 2002; Ward, 2008). A discard ban in Europe was adopted after more than 650,000 signed a petition calling for "discards" to be banned following a series of programs by television chef Hugh Fearnley-Whittingstall (De Vos et al., 2016).

Traditional approaches to bycatch management rely either on command-and-control measures such as gear restrictions or closed areas, or bycatch caps imposed at the fishery level

(Hall and Mainprize, 2005). These approaches, while sometimes effective at reducing bycatch, are often costly and inefficient (Abbott and Holland, 2013). Bycatch caps at the fishery level can spur a race for fish (before bycatch caps are reached) that can actually increase bycatch rates and reduce the amount of target species harvested (Holland and Ginter, 2001; Abbott and Wilen, 2010).

The use of near real-time data to guide the spatial distribution of commercial activities, sometimes referred to as dynamic ocean management (Lewison et al., 2015), is increasingly used in fisheries around the world (Little et al., 2015). It can be particularly effective when it can rely on data from third party observers on vessels who can rapidly transmit reliable information. However, when compliance is voluntary or hard to enforce it is important that vessels are incentivized to use this information to reduce bycatch. Otherwise cooperation can break down, particularly if an overall bycatch quota can close down a fishery or area (Abbott and Wilen, 2010).

Alternative approaches that allocate bycatch quotas to individuals or cooperatives can reduce costs and increase effectiveness of bycatch avoidance by effectively harnessing the knowledge and skills of fishers (Abbott and Holland, 2013; Abbott et al., 2015; Holland, 2018). These approaches can also spur investment in technology and information sharing systems (Pascoe et al., 2010). However, individual bycatch quotas (IBQs) can create substantial financial risk for fishers if bycatch is highly uncertain and variable (Holland, 2010). Quota markets in these cases may fail to redistribute quota effectively resulting in underutilization of both bycatch and target quota (Holland, 2016).

Holland (2010) showed that this risk can be reduced though the formation of voluntary risk pools where groups of fishers pool bycatch quota. Cooperative approaches have other advantages. They can motivate, or require, fishers to share information about bycatch hotspots and ways to avoid bycatch which can help reduce the cost and increase effectiveness of bycatch avoidance (Holland, 2018). Holland and Jannot (2012) notes, however, that risk pools, like other insurance products, can create problems of moral hazard and adverse selection. Enabling pool members to draw freely from pooled bycatch quota reduces incentives for vessels to exert sufficient care to avoid bycatch if doing so is costly. Risk pools may also be subject to adverse selection attracting vessels with higher bycatch risk or lower bycatch quotas relative to their risk. Thus risk pool developers may need to mandate, monitor, and enforce best practices for bycatch avoidance and may want to charge premiums related to bycatch risk and perhaps some form of co-pay or deductible that maintains sufficient incentives for vessels to avoid bycatch.

Although there are many examples of incentive-based and cooperative approaches to managing bycatch (see Holland, 2018), there are few empirical analyses that describe the mechanics of how bycatch reduction is reduced in these systems and how effective it is. This paper contributes to the literature by detailing and evaluating bycatch reduction measures for a particular case study that provides broader insight about how the characteristics of the industry group and management affect the choice and effectiveness of bycatch reduction measures implemented by industry cooperatives. In this paper we describe and analyze strategies used by industry groups to manage bycatch of rockfish and Chinook salmon in the United States Pacific whiting fishery off the coasts of Washington, Oregon, and California. Prior to 2011 individual vessels had weak incentives to avoid bycatch since the bycatch cap was a common pool. After 2011 vessels either had individual incentives created by individual quotas or operated under risk pool agreements as part of a formal cooperative that dictated best management practices for avoiding bycatch. We describe the structure of the Pacific whiting cooperatives and risk pools and the practices they used to reduce bycatch. We then evaluate whether actual fleet behavior is consistent with these practices and discuss reasons for differences in bycatch avoidance practices across sectors. We find differences in the bycatch reductions measures used across the different sectors that are attributable to differences in the way the vessels operate and the control and monitoring capabilities that cooperative entities have over individual vessels.

STRUCTURE OF THE PACIFIC WHITING FISHERY COOPERATIVES AND RISK POOLS

The Pacific whiting fishery uses midwater trawl gear and catches are comprised almost solely of Pacific whiting, but the fishery does have a small incidental catch of rockfish and salmon. Since 2005 the fishery has been subject to sector-specific bycatch caps for Chinook salmon (*Oncorhynchus tshawytscha*) and several rockfish species (widow rockfish–*Sebastes entomelas*, canary rockfish-*Sebastes pinniger*, darkblotched rockfish–*Sebastes crameri*, Pacific Ocean Perch (POP)-*Sebastes alutus*, and yelloweye rockfish-*Sebastes ruberrimus*). Chinook bycatch can include fish from endangered populations, and rockfish stocks were recovering from severe depletion though most are now rebuilt. Before 2011 these caps were applied at the sector level and would potentially shut down the entire fishery sector when reached. There was a separate cap for the shore-based and at-sea sectors, but the at-sea cap was a combined cap for the mothership and catcher-process sectors.

In 2011, a catch share system was implemented in the fishery. Catch shares provide exclusive catch rights for a share of the total catch to individuals or groups. For the shore-based component of the fishery an individual fishery quota (IFQ) system was implemented with 42% of the total Pacific whiting quota allocated to individuals and firms based on catch history (**Table 1**). The IFQs for the shore-based Pacific whiting are integrated into a larger IFQ system for the groundfish trawl fishery which includes quotas for the rockfish species taken as bycatch in the Pacific whiting fishery as well as other species targeted by other gears. There are not individual bycatch quotas for Chinook salmon bycatch, however, only a sector cap. The at-sea processing sector of the fishery is managed with cooperatives - one for the at-sea processors which are allocated 34% of the Pacific whiting allowable catch, and one for vessels delivering to floating processors called motherships which are allocated 24% of the Pacific whiting allowable catch collectively.

TABLE 1 | Whiting industry and cooperative structure and bycatch avoidance practices.

Sector	Shore-based	Mothership	Catcher-processor
Type of Harvest Privilege	Individual quotas	Group quota	Group quota
Risk Pool Membership	Voluntary – Not all vessels participate in risk pool	All vessels required to participate in risk pool	Vessel/company bycatch allocations
Information Sharing	Yes	Yes	Yes
Night Fishing Restriction	Yes	Yes	Yes
Year-round Closed Areas	Yes	Yes	Yes
Hotspot Closures	Yes	Yes	No
Move-on rules	No	Yes	No
Test tows	No	Yes	No
Monetary Penalties for Non-compliance	Yes	Yes	Yes

Each cooperative receives allocations (or caps) of rockfish and Chinook salmon to cover incidental catch. The catcher-processor sectors has operated contractually under a cooperative since 1997, and the 2011 regulatory action simply formalized the management approach in regulation. The mothership sector, however, had been fishing their whiting allocation competitively but created a single cooperative in 2011. Within the mothership cooperative, shares of the whiting allocation were assigned to individual vessel owners, however, the rockfish allocations were pooled, and a cooperative "risk pool" approach has been applied to manage bycatch.

Both the shore-based and at-sea sectors of the Pacific whiting fishery share the same problem: how to ensure that bycatch limits are not reached and shut down the fishery before the quota of Pacific whiting has been harvested. However the catcher-processor and mothership sectors are allocated collective bycatch quotas while the shore-based sector vessels have individual quotas. The at-sea sectors must create a bycatch management approach that includes all active vessels and can impose rules on all those vessels contractually. In contrast, the shore-based sector can limit access to its risk pool but cannot impose rules on those who don't join it. In the end, both groups implemented cooperative approaches that limit individual risk by pooling bycatch quota but still incentivizes bycatch avoidance by individuals. While all active vessels in the mothership sector are part of the mothership cooperative this is not the case for the shore-based fleet. The shore-based group must balance incentives to get more vessels to join with rules that ensure that riskier members are either excluded, controlled once in the risk pool, or compensate the rest of the pool for the additional risk they add. As the manager of the shore-based risk pool was quoted:

> The mothership co-op's task is to "individualize accountability while managing a common quota." the shore-based co-op's task is to "collectivize risk while maintaining individual accountability" (Blikshteyn, 2016).

In 2011 the mothership sector of the Pacific Whiting fishery formed a single cooperative that included the owners of 37 catcher vessels endorsed for operation in the mothership sector. The cooperative receives an allocation of Pacific whiting each year as well allocations of several rockfish species (POP, darkblotched rockfish, canary rockfish, and widow rockfish). The cooperative's internal contract (Fraser, 2011) allocates shares of Pacific whiting to each of the catcher vessels in proportion to the contribution to the cooperative's allocation made by NMFS (which is on the basis of the whiting catch history assigned to the Cooperative by its members). Individual allocations are transferable within the cooperative allowing for consolidation in the harvest operations, and many of the vessels do not fish in a given year. The number of vessels actually fishing ranged from 14 to 19 between 2011 and 2015. In recognition of the uncertainty and lack of control over bycatch, the cooperative pools the bycatch quota. The cooperative divides the whiting allocation into as many as four sub-annual pools with various start dates. Members must decide in advance how much of their whiting quota to allocate to each pool. Each pool then receives a share of the bycatch allocations in proportion to the proportion of whiting quota allocated to it. The individual vessels maintain their rights to the whiting quota submitted to the sub-annual pool, but the bycatch pool is a common pool. The co-op Agreement specifies that if a pool reaches its share of the bycatch prior to harvesting its whiting allocation, the members of the pool must cease fishing. Unused bycatch from each pool, other than the last pool of the year, is carried over to the next pool.

To ensure that vessels are avoiding bycatch, the mothership risk pool agreement implements a number of operational rules. These include: precautionary closures of past bycatch hotspots and in-season hotspot closures; restrictions on fishing at night (when the bycatch species tend to move up off the bottom increasing potential bycatch); and mandatory relocation of the fleets delivering to each mothership if a fleet's bycatch rate exceeds specified rates. Relocations are triggered either by 3 days rolling averages exceeding 125% of a base rate for a species (e.g., the ratio of total bycatch allocation to Pacific whiting allocation) or if the fleet bycatch rate in a single day is twice the base rate. Perhaps most importantly, the mothership cooperative requires members to share spatially explicit information about both whiting catches and bycatch. This is done through a company called Sea State, Inc., which receives this information directly from the fishery observer program (which places observers on all vessels) and processes it and relays it on to the fleet daily. Sea State identifies bycatch hotspots and designates time-area closures which vessels are obligated to avoid. The cooperative's manager can use observer data to monitor compliance with closures and other risk pool rules.

The bycatch avoidance practices of the catcher-processor sector are less clear. The catcher-processor cooperative produces an annual report that indicates that the cooperative contracts with Sea State, Inc., to monitor bycatch rates and authorizes it to impose in-season closures of bycatch hotspots, but there are no indications in these reports that this authority has been used. Reports indicate that individual vessels have kept bycatch with individual vessel allowances, and both bycatch and Pacific whiting catch are reported for each individual catcher-processor.

The shore-based sector risk pool also requires members to follow specified bycatch avoidance rules including prohibitions on night fishing and adherence to pre-season and in-season time and area closures (personal communication Dave Frazer, Risk Pool Manager). In addition it implemented a system of premiums, deductibles, co-payments and penalties that attempt to limit adverse selection and moral hazard. Risk pool members are required to make a minimum contribution of bycatch quota to the risk pool proportionate to the Pacific whiting quota they intend to fish (which they must declare in advance). The minimum contribution is the members' pro-rata share of the aggregate quota of constraining canary rockfish, widow rockfish, darkblotched rockfish and POP allocated to the member vessels relative to their aggregate whiting quota. The minimum pool commitment for yelloweye is the average amount of yelloweye quota allocated to a permit. For each of the bycatch species, other than yelloweye, 50% of the individual's commitment remains in a restricted account for their access and 50% goes into a reserve account for the risk pool. For yelloweye, which has a very small total quota, 100% goes into the risk pool reserve account. Members must first cover their own bycatch out of their own restricted reserve account but when that is exhausted can draw from the risk pool reserve account provided their average bycatch rate has not exceeded 120% of the base rate (the ratio of all members' bycatch quota for that species to whiting quota held). If that rate is exceeded, the vessel is required to stand down for 7 days or make an additional contribution of bycatch quota to the risk pool to bring their rate (of bycatch covered by the pool) down below 120% of the base rate. There are stricter criteria and longer stand-downs for yelloweye bycatch. Members who use bycatch in excess of what they contribute to the risk pool reserve account (and their own restricted account) can be compelled to pay an amount per pound of bycatch determined by the risk pool board. A funding mechanism enables the board to purchase additional bycatch quota to supplement the risk pool reserve account if necessary. Spatially explicit information on catch and bycatch for shore-based pool members is also collated and distributed by Sea State, Inc., (the same company doing this for the at-sea sector), but there is a delay in distributing this information because it relies on information not available until after vessels land. Captains are asked to enter preliminary data before starting a new trip. In addition to the individual incentives to reduce bycatch rates created by the cooperative's rules, individual vessel are also subject to limits on how much an individual vessel can catch of any species during the year regardless of whether they can acquire quota to cover it. Exceeding these vessel catch limits can result in the vessel being shut down for the remainder of the year or even longer.

ANALYSIS OF FLEET AND VESSEL BEHAVIOR AND OUTCOMES

Data

We use observer data collected by the West Coast Groundfish Observer Program and the At-Sea Hake Observer Program and fish tickets (landings records) compiled by PacFIN to evaluate outcomes and changes in behavior for the different fleets in the Pacific whiting fishery. This data includes tow-level information on catch, the location and time of the tow, the vessel, etc. For the mothership sector there is accurate information on the bycatch for each individual tow since observers sample from it when it is offloaded to the mothership. For the shore-based sector, vessels often make only 2–3 tows on a trip and the catch is mixed in the refrigerated seawater hold. Estimates of the catch of whiting per tow are available, but the bycatch is typically only known at the trip level and is documented in fish tickets.

Aggregate Bycatch and Bycatch Rates Over Time

Figure 1 shows bycatch rates per 100,000 pounds of whiting from 1994 to 2016. These rates are erratic and do not show any clear trends or changes following implementation of catch shares with exception of the shore-based sector for which bycatch rates for rockfish appear to have increased in recent years - though we do not undertake a formal times-series analysis to look for changes in trends or their causes here. Increases in catches of rockfish by the shore-based sector, particularly for widow rockfish, likely reflect increasing availability of quota pounds resulting from increases in the annual catch limits for those species. Widow rockfish was declared rebuilt in 2012, and the total annual quota allocation to the IFQ nearly tripled in 2013 and increased another 50% in 2015. Some vessels began targeting widow rockfish in 2015, and incentives to avoid it would have been low. Quotas for canary and darkblotched rockfish and POP remained small through 2016, but 40% or more of the quota pounds for these stocks in the shore-based sector went unused in all years except for Canary rockfish in 2015 when the quota was fully utilized. Vessels could lease quota pounds for these species to cover bycatch though quantities of quota available for lease were small with many fishers holding on to the small amount they had in case of unexpected bycatch. Quota pound prices exceeded ex-vessel value (price paid to vessels) for canary and darkblotched rockfish and POP (**Table 2**) suggesting they were seen as a constraint or at least potential constraint, despite the consistent surplus quota at the end of the year (Holland, 2016). Canary and darkblotched rockfish and POP have now all been rebuilt and their abundance appears to have increased substantially since 2011 which would also partially explain increases in bycatch rates.

In contrast to the shore-based sector, the allocations of rockfish species to the at-sea sectors did not increase over this period in proportion to total allowable catches and abundance, and they maintained very low bycatch rates for them. Industry representatives have also stated that they face a trade-off in avoiding Chinook salmon and some rockfish species which can cause one to rise if avoidance of the other is seen as a higher priority. These factors and the volatile and uncertain nature of bycatch makes identifying changes in bycatch rates associated with particular policies or behaviors problematic.

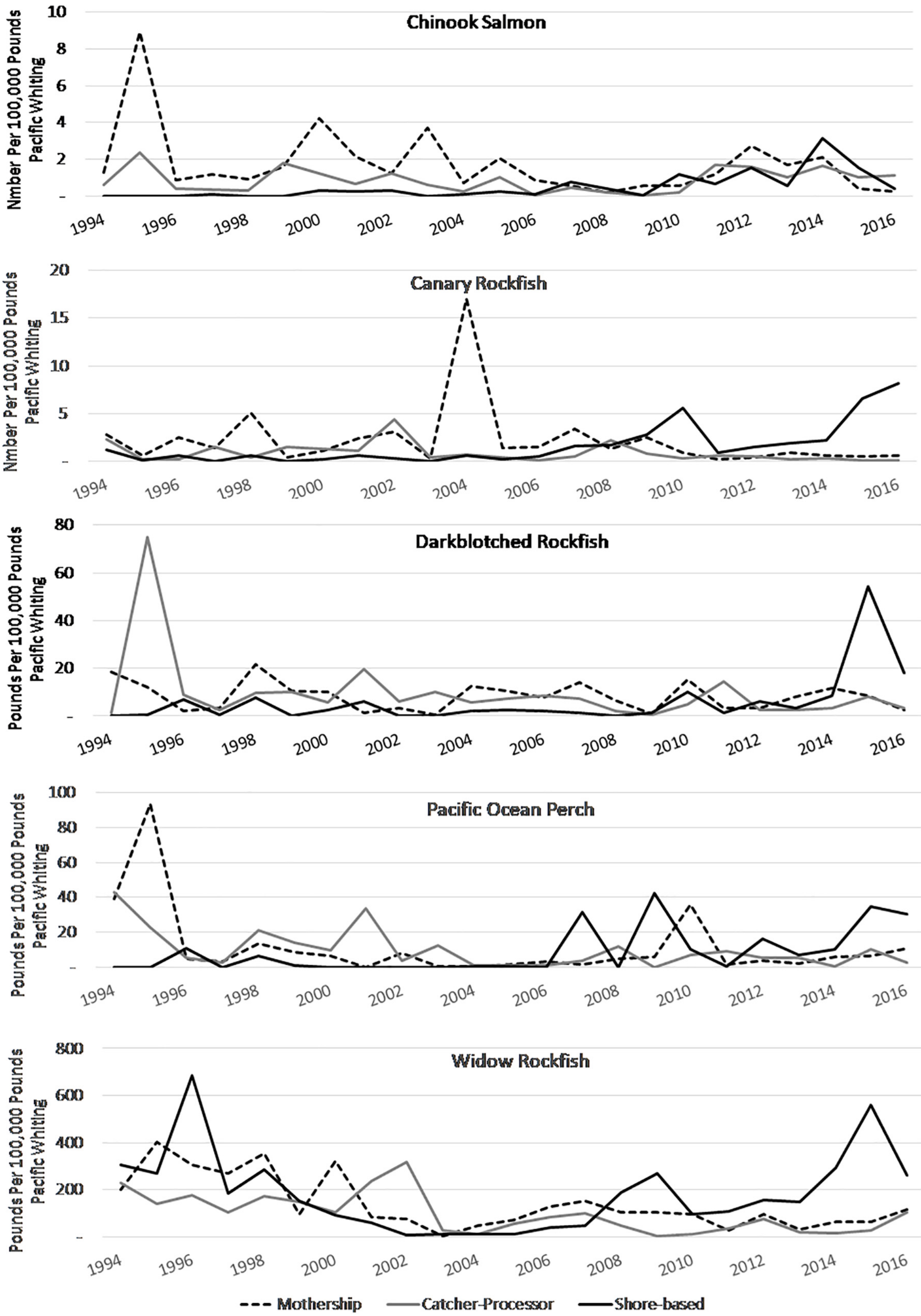

FIGURE 1 | Bycatch rates for different sectors of the US Pacific whiting fishery.

TABLE 2 | Ratio of quota pound price/ex-vessel price.

IFQ Species	2011	2012	2013	2014	2015	2016
Canary rockfish	2.24	2.91	6.18	3.88	2.05	2.75
Darkblotched rockfish	0.84	0.45	1.11	2.43	1.15	1.21
Pacific ocean perch	0.28	–	1.58	2.30	1.14	1.17
Widow rockfish	1.01	0.81	1.18	0.53	0.37	0.36

Changes in Behavior

Closed Areas

While it is difficult to determine whether or how much bycatch avoidance affected realized bycatch rates, we can look directly at whether and how fishing behavior was adapted to reduce bycatch. Little information is available about bycatch avoidance activities in the catcher-processor sector and it is not clear that behavior changed significantly after 2011. The catcher-processor sector had already been operating under a cooperative since 1997 and had been using Sea State to facilitate bycatch avoidance over that period.

In contrast, the mothership sector transitioned in 2011 from a race-for-fish to operation under a single cooperative with a highly structured agreement that included a number bycatch avoidance practices. The mothership sector of the fishery and the shore-based whiting risk pool all implemented self-imposed closed areas in locations where high bycatch rates had been experienced in the prior years. The mothership sector designated 9 precautionary area closures, totaling nearly 2000 km^2 which have been closed year round since the cooperative began operation in 2011 (Fraser, 2011). The mothership sector also authorized the risk pool managers to implement in-season closures in bycatch hotspots. Annual reports from the mothership cooperative indicate that these were used only a few times. The boundaries of the voluntary closures are not reported, thus it is not possible to verify whether the fleet fully complied with its own closures, but the cooperative's annual reports indicate that there have been no violations of the cooperative's agreements. The mothership cooperative manager could also shut down fishing once the seasonal pool of bycatch was exhausted. This occurred for at least one pool in most years.

The shore-based whiting risk pool also imposed year-round closures determined annually (Dave Frazer, personal communication November 2017), but the number and extent of closures is not available. There is no formal reporting on use of in-season closures by the shore-based risk pool but the risk pool manager indicates they have been used rarely if at all. However, vessels are required to share information about bycatch enabling others to voluntarily avoid these areas.

Night Fishing Restrictions

Both the mothership and shore-based cooperatives restrict night fishing during part of the year. We compared the proportion of tows taking place at night pre- and post-catch shares. For the mothership sector, between 1999 and 2010, 6.9% of tows took place between 10 PM and 5:30 AM while only 0.17% of tows took place in that time window between 2011 and 2014. For the shore-based vessels we did not have data on time-of-day prior to 2011, but between 2011 and 2014, only 0.58% took place during the night before September, 1.3% after September, and 0.89% overall. The catcher-processor sector apparently does not prohibit night-time fishing and there has been little change since 2011 with 25.3% of hauls taking place at night from 1999 to 2010 and 27.4% from 2011 to 2014.

Distance Moved

Move-on behavior is another important way in which vessels can reduce their exposure to bycatch. This method of spatial avoidance is closely related to area closures. Vessels experiencing a bycatch event can move to a new area for their next tow. When vessels learn of a bycatch event is an open question. In the case of the shore-based fleet, vessels may learn immediately on pulling their nets out of the water. For the at-sea fleets (both catcher-processors and motherships), there may be some delay before they learn the contents of their last haul, potentially until after the next haul has already begun.

We examined the contents of the previous haul on the distance moved between hauls. For motherships, we use the daily centroid of hauls for each motherships fleet of catcher vessels and model distance moved between days rather than between hauls. We utilize haul-level data from 1999 to 2014 and use vessel and year fixed effects in a generalized linear model with heteroscedasticity-robust standard errors. The log of distance moved in nautical miles since the last haul for haul h, by vessel i, in year y is the dependent variable, and explanatory variables include quantities of whiting and rockfish caught on the last haul (in metric tons) and an interaction of rockfish catch with the catch share categorical variable to determine if the distance moved in response to rockfish catch was greater once the catch share system began.

$$Dist\_move_{h,i,y} = \alpha_{i,y} + \beta_1 whiting_{h-1,i,y} + \beta_2 rockfish_{h-1,i,y} + \beta_3 (catchshare_y * rockfish_{h-1,i,y}) + \varepsilon$$

For each of the results, we see the expected behavior with respect to the target species catch: additional tonnage of whiting leads to shorter distances moved. In other words, vessels who have found the fish continue fishing in the same area. Move-on distance decreases by 0.62% per ton of whiting caught in the shore based fleet ($p < 0.00$), 1.00% per ton in the mothership fleet, and 1.78% per ton in the catcher processor fleet (**Table 3**).

The central question as far as bycatch is concerned is whether move-on distances increase when bycatch is encountered. We are particularly interested in whether these distances changed under the catch-share or cooperative programs described above. In the shore-based fishery, there is clear evidence of move-on behavior after a bycatch event. An additional ton of bycatch caught corresponds with an 11.5% increase in distance moved between hauls (**Table 3**). After the implementation of the catch share program, the point estimate suggests that this reaction to bycatch diminishes, consistent with the decreased risk exposure afforded by the catch sharing program, but these results are marginally statistically insignificant ($p = 0.11$).

In the mothership fleet, the cooperative implementation leads to clear evidence of increased move-on behavior. Absent the cooperative, an additional ton of bycatch correlated with a 20.3% increase in distance moved (p = 0.00) (**Table 3**). After the cooperative implementation, distance moved increases even more, by 59.4%, per ton of bycatch (p = 0.03). This result is consistent with the aim of the cooperative in increasing vessel-level bycatch avoidance incentives.

For the catcher-processor fleet, each ton of bycatch increased distances between hauls by 9.3% ($p < 0.00$) (**Table 3**). Post-2011 catcher-processor cooperatives increased this response, with each ton of bycatch caught increasing distance moved by 61.9% (p = 0.02).

In short, all sectors exhibit move-on behavior after bycatch events, and there is evidence of increased move-on behavior (e.g., moving further on average) after the institutional change for the at-sea fleets (mothership and catcher-processor).

HAUL DURATION

The final margin of bycatch avoidance we examined in the fishery was haul duration. Vessels can survey a new area for both target species and bycatch species by performing test tows. The distribution of distance moved is relatively smooth and does not follow a bi-modal distribution, so it is difficult to ascertain when vessels would consider an area "new." We designated new areas as those occurring either as the first tow of a trip for the shore-based fleet, the first tow after a period of inactivity for the at-sea fleets, and after a move-on distance above the 60th percentile for either fleet. The results presented below are robust when using either higher or lower thresholds for move-on behavior.

Again we use a utilize haul-level data from 1999 to 2014 and use vessel and year fixed effects in a generalized linear model with heteroscedasticity-robust standard errors. The regression have haul duration in minutes for haul h, by vessel i, in year y as the dependent variable and explanatory variables include: a categorical variable taking a value of one if the vessel was fishing in a new areas since the last haul (as described in the prior paragraph); new area interacted with a categorical variable taking a value of one if the haul took place in the catch share period (later than 2011); variables for the quantities of whiting and rockfish caught on the last haul, and an interaction of rockfish catch with the catch share categorical variable to determine if the decrease in duration of the subsequent tow in response to rockfish catch was greater once the catch share system began. We also include a categorical variable for first haul of the day for catcher processes only.

$$\begin{aligned} &Duration_{h,i,y} \\ &\quad = \alpha_{i,y} + \beta_1 newarea_{h,i,y} + \beta_2 (newarea_{h,i,y}{}^{*} catchshare_y) \\ &\quad + \beta_3 whiting_{h-1,i,y} + \beta_4 rockfish_{h-1,i,y} \\ &\quad + \beta_5 (catchshare_y{}^{*}\, rockfish_{h-1,i,y}) + \beta_6 firsthaul_{h,i,y} + \varepsilon \end{aligned}$$

For the shore-based fleet, we find that new areas resulted in 17-minute reductions in typical tow duration before implementation of the catch share program ($p < 0.00$) with an average tow length of 268 min (**Table 4**). This effect disappeared after 2011 (p = 0.02). The amount of whiting catch in the last haul results in shorter tows, though this may reflect the vessel capacity and not test tow behavior (most trips consist of three or fewer tows). Tows after bycatch encounters are 7 min shorter per ton (p = 0.06) before catch shares, increasing to 20 min shorter per ton (p = 0.02) after 2011.

In the mothership fleet, we see a similar effect. Mean tow duration over the sample was 202 min. New areas are associated with 32-minute shorter haul duration ($p < 0.00$) before 2011 (**Table 4**). Before 2011, a ton of rockfish catch was associated with a 14 min increase in the subsequent tow duration ($p < 0.00$). The point estimate suggests that this effect was reversed and bycatch events led to shorter subsequent hauls post-2011, but these results are not statistically significant (p = 0.16).

For catcher-processors, the evidence of decreased tow duration after a bycatch event is strongest in both practical and statistical terms. Typical haul duration in this fleet was 121 min over the sample (**Table 4**). The first tows were typically 16 min shorter, increasing to 23 min shorter after catch shares were

TABLE 3 | Fixed effects models of distance moved by sector.

Explanatory variable	Shore-based	*p*-value	Mothership	p-value	Catcher-processor	p-value
Last Haul Whiting (metric tons)	−0.0062	<0.001	−0.0100	<0.001	−0.0178	<0.001
Last Haul Rockfish (metric tons)	0.1145	<0.001	0.2032	0.002	0.0928	0.002
Rockfish (metric tons) × Catch Share Program	−0.1090	0.109	0.3909	0.025	0.5270	0.025

Dependent variable is log(distance moved nautical miles). The constant is not shown as this is a fixed effects model and constants vary by vessel.

TABLE 4 | Fixed effect models of haul duration by sector.

Explanatory variable	Shore-based	*p*-value	Mothership	*p*-value	Catcher-processor	*p*-value
New Area	−16.73	<0.001	−31.85	<0.001	−16.36	<0.001
New Area × Catch Share Program	16.60	0.022	0.82	0.955	−6.69	0.071
Last Haul Whiting	−1.56	<0.001	−0.36	<0.001	0.42	<0.001
Last Haul Rockfish	−7.28	0.061	13.79	0.002	−1.70	0.084
Rockfish × Catch Share Program	−12.91	0.024	−36.79	0.162	−40.69	0.002
First Haul of the Day	*n.a.*		*n.a.*	–	14.84	<0.001

Dependent variable is haul duration in minutes.

implemented in 2011. A ton of rockfish was associated with a 2 min decrease in tow duration before 2011, increasing to a 42 min decrease after 2011. Tows were also shorter if there was rockfish caught on the previous tow, particularly after the catch share program was implemented ($p = 0.00$).

DISCUSSION

The three sectors of the Pacific whiting fishery all face a common problem of limiting bycatch of rockfish and Chinook salmon while targeting Pacific whiting. All three have implemented cooperative approaches to managing bycatch with many similar practices, but also some distinct differences that reflect differences in their operational characteristics, homogeneity of membership, and ability to exercise centralized control over vessel operations.

A primary advantage of risk pools (in addition to access to quota) is information sharing that enables individuals to make better decisions about when and where to fish. All three sectors use a private third party provider, Sea State, Inc., to share and collate information about bycatch hotspots to enable near real-time avoidance of these areas. All three sector have imposed rules upon their members that limit fishing at particular times or places, but there are some differences in the rules imposed that reflect differences in the flexibility of the vessels. For example, move on rules and test tows are not required by the shore-based risk pool which makes sense since vessels average only two tows per trip and vessels trip duration is strictly limited once the first fish is brought on board since quality deteriorates rapidly. In contrast the mothership sector which has fleets of vessels fishing cooperatively with a mobile floating processor can more easily implement test tows (i.e., by having one vessel make an initial tow before others begin fishing) and can take time to move locations without fear of spoilage since the fish is being processed at sea.

The sectors also differ in terms of how they incentivize individual vessels to avoid bycatch beyond simply following specified rules, and there are differences in what rules are imposed. The shore-based sector risk pool has looser control over individual vessels and consequently more issues with moral hazard and adverse selection than the mothership sector. Perhaps for this reason, it relies on premiums and co-payments and deductibles (all paid in-kind with quota), and also provides more limited coverage of bycatch risk. The mothership sector risk pool includes all vessels in the sector so does not face an adverse selection problem, and it exercises substantial control of vessels at the fleet level and can effectively impose bycatch avoidance behavior which essentially eliminates moral hazard. Consequently they do not rely on incentives at the individual vessel level, but do impose quarterly bycatch quotas that ensure vessels and motherships fishing in each quarter do not impinge on opportunities for those fishing later in the year.

The lack of discernable change in bycatch rates following implementation of catch shares and risk pools is likely due to the erratic and uncertain nature of bycatch and the trade-offs faced by vessels between different bycatch species (e.g., avoiding one increases risk of catching another). However it is clear that the fleets have made substantial efforts to develop institutions, technology and rules to avoid bycatch. Bycatch might have been substantially higher without this cooperation, but it is not possible to discern whether or how much it might have differed. Notably, the biomass of several of the rockfish stocks has increased substantially over the last few decades as these stocks have been rebuilt. Thus even constant bycatch rates would reflect increased avoidance.

Examining margins of adjustment, there is clear evidence of reduced night-fishing after cooperative institutions for the mothership whiting fleet. There is also evidence of increased bycatch avoidance for the at-sea fleets along other margins: move-on behavior after a bycatch event and test-towing in new areas or after a bycatch event. For the shore-based fleet, there is evidence that the fleet stopped test-towing in new areas but reduced tow duration after a bycatch event with the implementation of its bycatch risk pool.

Although risk pools have imposed what might be considered traditional command-and-control regulations on themselves (e.g., time and areas closures), many of approaches implemented by the risk pools probably could not have been implemented by regulators either because of the slowness of the rule making process (e.g., in-season closures) or because of regulators could not require vessels to share information. Risk pools are able to cooperatively decide on a carefully designed set of year-round closed areas that limit bycatch risk without closing down key harvest areas. They can also impose short-term area closures in bycatch hotspots quickly relying on shared information and without a formal rulemaking process.

A key characteristic of the bycatch problem in this fishery is the rarity, uncertainty and lumpiness of bycatch which makes it difficult for individual vessels to meet strict performance standards like maximum bycatch rates or individual quotas. In recognition of this, none of the sectors rely solely on individual incentives such as individual bycatch quotas, and two of the sectors pool bycatch quota. While the catcher-processor sector imposes vessel-level bycatch allowances, these vessel are extremely mobile and have greater ability to control bycatch over the course of a season. They can also trade bycatch allowances within the cooperative, and the cooperative has a long history of working cooperatively to avoid bycatch.

DATA AVAILABILITY STATEMENT

Restrictions apply to datasets. Analysis relies on observer data from fisheries which is confidential and requires negotiating a data access agreement.

AUTHOR CONTRIBUTIONS

Both authors participated in data analysis and writing of the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.