The effect of rights-based fisheries management on risk taking and fishing safety

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Commercial fishing is a dangerous occupation despite decades of regulatory initiatives aimed at making it safer. We posit that rights-based fisheries management (the individual allocation of fishing quota to vessels or fishing entities, also called catch shares) can improve safety by solving many of the problems associated with the competitive race to fish experienced in fisheries around the world. The competitive nature of such fisheries results in risky behavior such as fishing in poor weather, overloading vessels with fishing gear, and neglecting maintenance. Although not necessarily intended to address safety issues, catch shares eliminate many of the economic incentives to fish as rapidly as possible. We develop a dataset and methods to empirically evaluate the effects of the adoption of catch shares management on a particularly risky type of behavior: the propensity to fish in stormy weather. After catch shares was implemented in an economically important US West Coast fishery, a fisherman's probability of taking a fishing trip in high wind conditions decreased by 82% compared with only 31% in the former race to fish fishery. Overall, catch shares caused the average annual rate of fishing on high wind days to decrease by 79%. These results are evidence that institutional changes can significantly reduce individual, voluntary risk exposure and result in safer fisheries.

catch shares | occupational safety | rights-based fisheries management | risk | sustainable fisheries

Occupational health and safety regulations are often instituted in response to market failures that result in a misalignment of workers' risk exposure with their individual preferences (1). The principal justifications for regulatory intervention include excessive risk taking by workers who may not fully understand or recognize the risks they face (imperfect information) or do not bear the full cost of adverse safety outcomes (moral hazard) (2, 3). Labor market frictions and societal concern about the health and safety of those in high-risk occupations provide further motivation for worker protections (3, 4).

The commercial fishing industry is affected by these types of market imperfections and is also characterized by potentially high pecuniary rewards for the physical risks involved in fishing. Safety regulations were developed in response to this recognition, as well as the observance of high fatality rates among fishermen (5). In the commercial fishing industry, workplace safety regulation and research has focused on technical solutions such as requirements to carry emergency equipment, participate in safety trainings, and obtain vessel safety examinations (5–9). However, commercial fishing is still one of the most dangerous professions, with an annual average fatality rate of more than 30 times the US average. Despite decades of voluntary and regulatory fishing safety initiatives, the fatality rate has decreased only marginally and has not decreased compared with the average rate for all US workers (Fig. 1) (10, 11).

Fishermen are often characterized as "risk-loving," drawn to fishing for the adventurous nature of the profession (12–14) and thus unwilling to abide by safety regulations (15). However, less attention has been paid to the fact that fisheries management itself can create a market failure—a lack of property rights can create a misalignment of economic incentives that can escalate the risks associated with commercial fishing. Historically, many fishing fleets operated under open-access conditions, characterized by little oversight. Charged with reducing the extent of resource depletion, fisheries managers responded by limiting effort in the fishery, often by restricting the length of fishing seasons (16). These regulations tend to create a perverse incentive to increase fishing power to catch the maximum amount of fish in the shortest amount of time. Harvesters have the incentive to outcompete others by expanding vessel size, vessel speed, the amount of gear, number of crew, or making other costly capital investments to compete in derby-style fisheries that have become known as the "race to fish" (17, 18). In such fisheries, it is commonplace for fishing seasons to be reduced to only a few days in an attempt to limit harvest to a sustainable level. Furthermore, fishermen have the incentive to participate in around-the-clock fishing in all weather conditions, overload their vessels, and ignore maintenance problems to maximize catch. These behaviors contribute considerably to the dangerous nature of commercial fishing.

Fisheries management also has the capacity to correct this market failure: "catch shares," a rights-based fishery management strategy that allocates a specific portion of the total allowable fishery catch to individual entities, can reduce or eliminate the incentive to race to fish (17, 19). Rather than maximizing the number of fish caught in the open season, under catch shares harvesters have the incentive to maximize the value of their individual allocation of fish (20). One of the many outcomes of catch shares has been a lengthening of the fishing season and an associated decrease in the speed and intensity of fishing (21–23). Under catch shares, fishermen no longer have the incentive to work without rest, delay vessel repairs, and fish in dangerous

Significance

Commercial fishing is a dangerous occupation despite decades of regulatory initiatives aimed at making it safer. We posit that the individual allocation of fishing quota can improve safety by solving many of the problems associated with the competitive race to fish, which manifest themselves in risky behavior such as fishing in poor weather. We present a previously unidentified approach to evaluation: estimating the change in the propensity to start a fishing trip in poor weather conditions as a result of the management change. We chronicle a revolution in risk-taking behavior by fishermen (a 79% decrease in the annual average rate of fishing on high wind days) that is due to the change in economic incentives provided by rights-based management.

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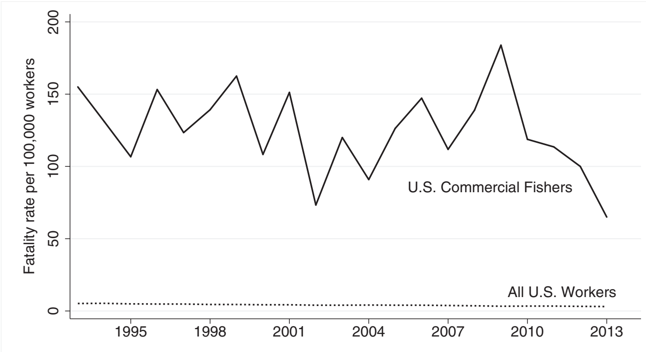

Fig. 1. Annual fatality rates of fishers and all workers in the United States. Figure was created with data available from the Bureau of Labor Statistics. Note: 1993 is the first year in which data are available online.

weather conditions (24, 25). Thus, this shift in incentives has the potential to make commercial fishing safer.

There is some evidence that catch shares management can decrease fatality rates and search-and-rescue missions in fisheries (26). However, obtaining robust, causal statistical estimates of the effect of policy on events that are rare (such as deaths, vessel disasters, or search-and-rescue missions) is notoriously difficult (27). In addition, events like these do not fully characterize the risky nature of fisheries. Near misses and nonfatal injuries are underreported, and rate calculations often suffer from a lack of data—number of crew, days at sea, hours worked, and even the number of participants are not tracked for many fisheries (6, 28).

We take a previously unidentified approach and focus on understanding and empirically investigating the underlying risk-taking behavior of fishermen and the effect that fisheries management can have on the incentives to voluntarily expose oneself to different levels of risk. Decreased risk exposure leads to safer fishing. Fishermen make many choices that affect their exposure to risk, but one of the most significant factors that commercial fishermen face is weather (29, 30). Severe weather conditions contributed to 61% of fatal vessel accidents in the United States from 2000 to 2009 (31) and 80% of fatal accidents on the US West Coast for the same time period (30). The propensity to fish in poor weather conditions is a proxy for risk exposure.

To investigate the impact of a change from a race to fish fishery to catch shares management on fishing safety, we focus on the propensity to start a fishing trip in poor weather conditions. We develop a dataset using a particularly data-rich fishery: the West Coast sablefish fixed gear fishery. The characteristics of the fishery allow a comparison between a treatment sector of the fishery (the sector that was subject to the management change) and a control sector (sectors that were not affected by the management change).

The largest sector of the sablefish fixed gear fishery is the primary fishery. It receives about 32% of the total annual commercial sablefish catch limit. Beginning in 1994, the sector was managed with license limitations (only vessels with a license could fish) and a season length set by managers to limit over-exploitation. This management resulted in extremely short, derby-type fishing seasons. In 2001, the fishery transitioned to a type of catch shares where individual vessels were allocated a tradeable portion of quota [individual transferable quotas (ITQs)], based on their historical participation in the fishery. As a result, the season lengthened from an average of 9 d (1994–2000) to 213 d (2004–present). Two smaller sectors of the fishery did not undergo such management reforms and have been managed with restrictive trip limits (i.e., maximum daily catches) for the entire time period (1994–present), providing a comparison group for whom fishing gear, species, geographical region, and many of the participants are the same (*SI Appendix*, section S1). Any unobserved shifts in the propensity to fish in poor weather, due to the influence of safety trainings or other types of Coast Guard regulations, for example, will have also occurred in the comparison "trip limit" fishery. In addition, because we follow the same set of vessels over time, vessel fixed effects can be used to eliminate the effect of time-invariant vessel characteristics such as length, hold size, or fishing power, as well as characteristics of the fishermen, such as skill, experience, or individual preferences over risk. We use a difference-in-differences specification with individual vessel fixed effects to statistically isolate the effect of the change in the management regime on the annual proportion of fishing trips that occurred on high wind days (32). Daily weather data are combined with the estimated date and location that each vessel's fishing trips began. The "pre-ITQ" management regime includes 1994–2000 and "post-ITQ" includes 2001–2012. High wind days are correlated with higher waves, stormy conditions, and correspond roughly to small craft advisories issued by the National Weather Service. We aggregate the daily data to the annual level, to obtain an annual average fishing rate on high wind days for each vessel. This specification empirically identifies the effect of the ITQ program on the average fishing rate in high winds, assuming that the trip-limit fishery and the primary fishery would have evolved similarly over time in the absence of the introduction of the ITQ program in the primary fishery (*SI Appendix*, section S4.4).

We also estimate the change in individual risk-taking behavior by modeling fishermen's repeated daily fishing choices. Physical risk and financial reward (i.e., the catch expected for a particular fishing trip and the market value of that catch) vary over time, and fishermen make tradeoffs between risk and profits when they decide to start a fishing trip. We use the panel of data described above, disaggregated to the daily level for 1994–2012, for the nearly 400 vessels in the primary fleet only. We model their daily fishing decision as a fixed-effects logit model where the decision to start a fishing trip on a particular day is a function of an indicator variable that designates either high winds or low winds at the vessel's port of departure and the revenue expected from taking a fishing trip. Expected revenue is the product of dock-side fish prices and expected catch per trip. The coefficients estimated in the model can be used to calculate the marginal rate of substitution between risk and financial gain; the ratio of the estimated coefficient on high winds to the estimated coefficient on expected revenue measures the compensation (in terms of dollars of expected revenue) that would be required for a fishermen to begin a trip on a day with high winds (33).

Results

By 2001, the primary sablefish fishery on the West Coast had been fully transitioned from a management system that limited exploitation by controlling the length of the fishing season to one that limited exploitation through a system of catch shares (*SI Appendix*, section S1). Our estimates indicate that the average annual rate of fishing on high wind days decreased dramatically as a result. Controlling for the changes that occurred independently of the management change via the difference-in-differences specification with individual fixed effects, the average annual rate of fishing on high wind days decreased by 0.428 or 79% (Fig. 2; $P = 0.000$). Unobservable shifts in the propensity to fish in poor weather that are not accounted for in the vessel fixed effects would have also occurred in the comparison trip limit fishery. The full regression output is available in *SI Appendix*, Table S4.

The results from modeling the daily fishing participation choices of each vessel in the primary fleet show that the average daily fishing rate decreased substantially post-ITQ implementation. The probability of beginning a fishing trip on a given day decreased by 85% ($P = 0.000$; Table 1; odds ratios available in *SI Appendix*, Table S5), as expected given the increase in season length.

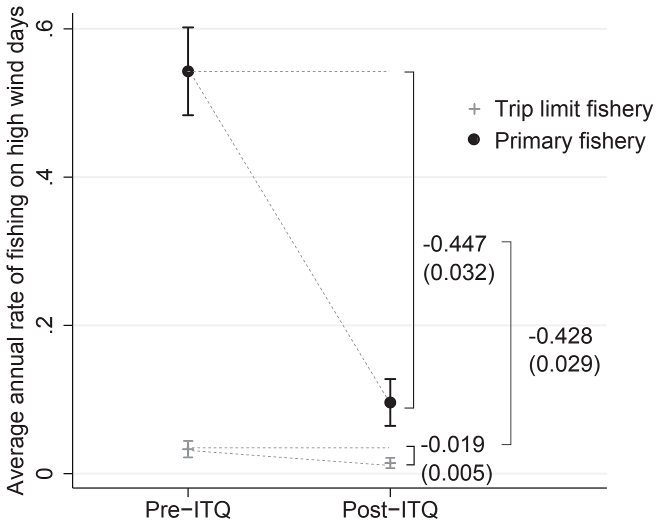

Fig. 2. Change in the annual average rate of fishing on high wind days. Estimates result from difference-in-differences regression of the annual vessel average rate of fishing on high wind days. Individual fixed effects included. Bars show 95% CIs around the estimates. SEs in parentheses. Number of observations: 5,396. $R^2 = 0.50$.

Pre-ITQ, expected revenue had no effect on the probability of starting a fishing trip. This result is consistent with fishermen's incentives in a derby fishery: any delay would result in the fish being caught by someone else. Post-ITQ, higher expected revenue had a positive effect on the probability of starting a trip. High winds had a negative effect on the probability of starting a fishing trip, but the effect increased after the ITQ program. In the pre-ITQ period, a high wind day caused a 31% decrease in the probability of taking a fishing trip, from a mean rate of 24% ($P = 0.000$; Table 1). Post-ITQ, a high wind day caused an 82% decrease in the probability of taking a fishing trip, from a mean rate of 3.5% ($P = 0.000$; Table 1). For the pre-ITQ period, the marginal rate of substitution between revenue and risk cannot be calculated because the coefficient on expected revenue is not significantly different from zero. Post-ITQ, the marginal rate of substitution is $33,000, implying that, on average, a fisherman would require three times the mean expected revenue per trip of $11,000 to fish on a high wind day (Table 1).

These results are indicative of a transformation of the incentive structure fishermen face, from one in which they must fish almost regardless of conditions to one in which they make rational tradeoffs between the risks involved with fishing in poor weather and the potential revenue to be gained.

Catch shares affect the incentives that fishermen face in many ways, and a variety of confounding mechanisms could be contributing to the estimated effect. Many of the intensive-margin behavioral changes that have been observed in other catch shares fisheries, such as targeting higher value fish (larger, higher quality, etc.), utilization of byproducts, or changing product types (21, 34, 35) have not occurred in this fishery (36). This lack of change is likely due to the characteristics of the market for West Coast sablefish; it is sold almost exclusively as a frozen, minimally processed product to Japan. Another of the most immediate results of catch shares is often consolidation, whether through vessel or permit buyback programs, or permit sales and quota trading (34). Although there was no buyback program, the number of active vessels in the primary fishery fell by about 30%. Vessels that stopped fishing were smaller on average and had the associated characteristics of lower catch per trip and more trips per year. In addition, there was a change in the spatial distribution of fishing: 56% of the vessels that exited the primary fishery fished in California compared with 27% in Oregon and 16% in Washington (Table 2). If the vessels that exited the primary fishery were less risk averse or more likely to take trips in poor weather, the estimated impact of the ITQ program on risk-taking behavior (Fig. 2) would be overstated, especially if some of the vessels continued to fish in the trip-limit fishery only.

We tested for variation in the propensity for risk taking across vessel size and for vessels that fished in California in the pre-ITQ period (Table 2). Smaller vessels are more susceptible to the risks associated with strong winds, large waves, and other stormy weather conditions. Vessels fishing in California may be more or less risk averse because of other, unobservable factors (how far off the coast they are fishing, for example). We find that the average aversion to high winds in the pre-ITQ period is similar for large and small vessels: both groups were about 36% less likely to start a trip on a high wind day. Smaller vessels had a higher mean probability of taking a trip because they can store less fish, meaning that their trips are shorter and they must make more trips to catch the same amount as a larger vessel. Vessels that fished out of California ports were somewhat more risk averse than those that fished from Washington and Oregon. California vessels also tended to be smaller; hence, their mean probability of starting a trip is higher. These results imply that small vessels and those that fished in California in the pre-ITQ period may have been slightly more risk averse than average. Finally, we estimate the model for vessels that exited the fishery after the ITQ, and for those that remained. A high wind day was associated with a 63% decrease in the probability of fishing for the set of vessels that exited compared with a 25% decrease among those vessels that remained (Table 3). This pattern of consolidation means that our estimate of a 79% decrease in the average annual rate of fishing on high wind days could be biased downward. Had the risk-averse vessels that left the fishery

Table 1. Changes in the probability of taking a fishing trip resulting from the fixed effect logit model of the probability of fishing

		Effect of $1,000 increase in expected revenue		Effect of a high wind day			
Period	Mean probability of taking a trip	Change in probability	Estimated coefficient	Change in probability	Estimated coefficient	Marginal rate of substitution	Mean revenue per trip ($2012)
Pre-ITQ	23.8%	—	−0.002	−31.3%	−0.376***	—	14.8
Post-ITQ	3.5%	4.3%	0.042***	−82.0%	−1.387***	33.0	11.0
Percentage change	−85.3%						

Number of observations: 223,976. Vessel fixed effects included. Marginal rate of substitution and mean revenue are in thousands of 2012 dollars.
***$P < 0.001$.

Table 2. Means (SDs) of primary and trip-limit fishery vessels before and after ITQ

	Pre-ITQ		Post-ITQ	
Characteristic	Primary	Trip limit	Primary	Trip limit
Number of vessels	130.8 (9.8)	165.8 (9.8)	89.8 (8.4)	143.3 (13.5)
Vessel length (ft)	43.1 (11.3)	39.7 (10.5)	45.6 (11.4)	37.3 (10.4)
Participate in both sectors (%)	70.8 (7.8)	56.0 (2.7)	54.7 (9.1)	34.1 (4.5)
Number of trips per year*	2.7 (2.2)	17.3 (21.5)	6.3 (4.6)	10.3 (11.3)
Trip length (d)	3.0 (2.2)	1.5 (1.0)	3.2 (2.2)	1.3 (0.7)
Landed fish per trip (1,000 lbs)	9.8 (9.3)	2.1 (5.9)	6.9 (7.3)	0.9 (1.7)
Revenue per trip (1,000 $)	19.4 (21.2)	3.8 (15.0)	18.9 (23.3)	2.1 (5.0)
Percent of effort in California	32.8 (3.5)	47.7 (12.3)	17.7 (4.2)	45.1 (7.5)

*Number of trips for the primary fishery is in the regular season only (excludes mop-up season trips).

remained, the effect may have been even larger (*SI Appendix*, Table S4).

Discussion

While often glamorized for their fortitude, commercial fishermen are one of the most at-risk groups in terms of occupational hazards. Fishing safety policies generally address one of two objectives: reducing the probability of death or injury in the event of an accident or reducing the probability of accidents. Limited empirical evidence suggests that regional fishing safety policy in the United States has been marginally effective in improving on the first objective (10, 31). Most policy intended to reduce risk exposure, however, tends to attempt to tell fishermen how to fish, advice that is poorly received in such an adventurous and fiercely independent lot.

Catch shares alter the incentives that underlie fishermen's decisions. In the fishery considered here, management prior to catch shares involved limiting the season length to restrict total harvest. This management strategy is not uncommon in the United States and around the world. Often, season length restrictions make the risk-reward tradeoff essentially degenerate: by delaying a trip, profits can only be lost. In fact, fishermen have been observed maximizing effort through every margin available to them: forgoing sleep or vessel repairs, overloading vessels, or removing safety equipment in favor of additional fishing gear—behavior that is risky, but not unexpected given their economic incentives (5). The incentives are present regardless of the legality of such actions, necessitating substantial enforcement effort and penalties to prevent (37). Technological safety regulations, such as a requirement to carry emergency equipment, cannot be expected to be markedly effective in preventing accidents in such a landscape.

Catch shares, a management system not directly designed to improve safety in its inception, corrects the market failure that contributes to the dangerous nature of commercial fishing. Catch shares change fishing incentives such that fishermen themselves decide to expose themselves to less risk. In the West Coast sablefish fishery, this has resulted in a dramatic decrease in risk-taking behavior by fishermen. The average annual rate of fishing on a high wind day decreased by 79% as a result of the change in economic incentives provided by rights-based management. After catch shares, a vessel would have to expect over three times the expected revenue to fish on a high wind day than to fish on a day without high winds. Consolidation resulted in a 30% reduction in the size of the fishing fleet. The vessels that exited were smaller, more likely to fish from California ports, and more risk averse than vessels that remained in the fishery. Without this consolidation, the decrease in the average annual rate of fishing in high winds may have been even larger.

It is worth noting that the dramatic change in the propensity to fish in poor weather measured for this particular fishery may be at the upper end of the distribution of expected effects. The West Coast sablefish fixed gear fishery is a single-species fishery that transitioned from a condensed derby-style fishing season of only a few days to a 7-mo season in a region with relatively good weather. The vessel allocations are tradeable, but with restrictions and relatively low quota accumulation limits (*SI Appendix*). The catch shares program in the West Coast sablefish fixed gear fishery was very effective in eliminating the race to fish. There are many situations in which the competitive nature of the fishery may not be completely eliminated. If prices, the size of

Table 3. Changes in the probability of taking a fishing trip by size of vessel, location of fishing, and whether or not the vessel exited the primary fishery after the ITQ

			Effect of $1,000 increase in expected revenue		Effect of a high wind day	
Vessels	Period	Mean probability of taking a trip	Change in probability	Estimated coefficient	Change in probability	Estimated coefficient
<43 ft	Pre-ITQ	29.0%	—	−0.002	−36.4%	−0.452***
≥43 ft	Pre-ITQ	17.7%	2.0%	0.020**	−36.1%	−0.447*
Fished in CA	Pre-ITQ	29.3%	—	0.001	−37.0%	−0.462***
Fished in OR and WA	Pre-ITQ	21.5%	—	0.003	−33.8%	−0.412*
That exited	Pre-ITQ	21.9%	—	0.028	−63.8%	−1.017***
That remained	Pre-ITQ	24.1%	—	−0.003	−25.0%	−0.287***
That remained	Post-ITQ	3.4%	4.3%	0.042***	−75.0%	−1.386***

Estimates result from the fixed effect logit model of the probability of fishing. Number of observations: vessels <43 ft, 100,898; vessels ≥43 ft, 123,078; vessels that exited the primary fishery, 1,689; vessels that remained in the primary fishery, 222,287; vessels fishing in California, 54,603; vessels fishing in Oregon and Washington, 168,228. Vessel fixed effects included.
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

fish, or the catchability of fish (due to the concentration of biomass, for example) are highest during a short time in the fishing season, harvesters may still compete for the highest-value or easiest-to-catch fish. Other compounding factors include bycatch restrictions or bycatch quota that is constraining, fisheries in which quota is mainly leased rather than fished by the quota owners, or fisheries in which the timing of fishing and deliveries is controlled by processors (35, 38–40). Although the extent of season compression and post-ITQ expansion is not unprecedented [e.g., Alaska sablefish (41), Alaska halibut (42), British Columbia halibut (21), and Alaska crab (43) ITQ programs], in other programs the difference in season length may not be as extreme. In these cases, a more nuanced effect can be expected. The complexity of the incentives harvesters face before and after catch shares is an important consideration.

According to data from the US Coast Guard, the average annual incident rate (safety incidents per 1,000 vessel days at sea) in the West Coast sablefish fixed gear primary fishery fell from 0.8 in 1994–2000 to 0.1 in 2001–2012, an 87% decrease ($P = 0.006$) (44). Thus, the behavioral changes we describe appear to be consequential in terms of occupational safety outcomes, even with the statistical limitations of establishing identification and robust estimates using traditional types of occupational health data. In this study, we empirically demonstrated that the changed incentive structure faced by fishers operating under a catch share system caused them to take fewer weather-related risks. In a derby fishery, the risk/reward tradeoff of forgone catch is identical whether the source is a weather-related delay in fishing, a pot left on the dock to not overload a vessel, or space taken up by survival suits or other safety equipment rather than captured fish. Thus, we expect the effect of catch shares on these other margins of risk exposure to be similar, the outcome of which will quite credibly be a decrease in injuries, pollution events, vessel losses, search-and-rescue missions, and deaths from fishing accidents.

Methods

Data.

Fishery data. Fishing data for the analysis were acquired from landings records from 1994 to 2012 for the primary and trip-limit fisheries, maintained by the Pacific Fisheries Information Network (PacFIN; www.psmfc.org). PacFIN is a federally funded project that focuses on fisheries data collection and information management for the Pacific Coast and combines data from federal, state, and Canadian sources. The data are available from PacFIN provided a researcher signs a nondisclosure agreement and meets other requirements for access. Landings data contain the date, location, type of gear used, quantities of each species, and revenue received for each species of each delivery. A total of 499 vessels participated in either the primary or the trip-limit fishery from 1994 to 2012, although many did not participate in all years. One hundred nineteen vessels participated only in the trip-limit fishery, and 48 vessels participated only in the primary fishery. Summary statistics for each sector, before and after the ITQ, are provided in Table 2. In the post-ITQ period, fewer vessels participated, but catch and revenue per trip were higher in both sectors, and annual catch per vessel was higher in the primary fishery. The proportion of effort in California decreased after ITQs in the primary fishery but was unchanged in the trip limit fishery. The majority (95%) of this shift was due to consolidation (vessels from Oregon and Washington buying or leasing quota from California-based vessels) rather than California-based vessels moving north to fish for sablefish.

Estimation of trip start dates and trip start locations. Trip starts (location and date) were determined from West Coast Groundfish Observer Program data (www.nwfsc.noaa.gov/research/divisions/fram/observation/). In the sablefish fishery, ∼20% of trips had federal observers on board for the time period 2002–2012. For unobserved trips, trip length was modeled using the Observer data (*SI Appendix*, Table S1; in-sample $R^2 = 0.84$, RMSE = 0.43). Trip length was a function of vessel size, catch, gear, and sector. The Observer program data collection began in 2002, so estimates of all trip lengths before 2002 are out-of-sample estimates. Ninety-eight percent of observed trips departed and landed in the same port, so departure locations for unobserved trips were assumed to be the same as the location of landing.

Estimation of expected revenue. Expected revenue is the product of dockside sablefish prices and expected catch of sablefish per fishing trip [$E(C_{mit})$], which are assumed to be independent. Prices were estimated using a 15-d moving average of past prices received by all vessels in the primary fleet by the state of delivery (*SI Appendix*, section S2.2). Expected catch per trip was modeled parametrically

$$E(C_{mit}) = \alpha + \gamma' \mathbf{x}_{it} + \varepsilon_{it}, \quad [1]$$

as a function of vessel capacity, month, management regime, gear, and the vessel's remaining quota. The results for the expected catch regression are shown in *SI Appendix*, Table S2.

Weather data. Fishing in poor weather conditions has been shown to contribute to the probability of accidents and safety incidents (45). Wind speed is the most appropriate indicator of weather conditions that is attainable for the entirety of the time series (daily observations from 1994 to 2012) and at a meaningful spatial scale. Wind speed was estimated using reanalysis surface fluxes generated by the National Center for Environmental Protection (NCEP; www.esrl.noaa.gov/psd/). Reanalysis wind speed data are available in 2° grids in 6-h intervals. We calculated the maximum daily 6-h average wind speed at each grid cell and then calculated the inverse distance weighted average from the four cells nearest to the port of departure of each fishing trip in our dataset. NCEP reanalysis surface flux underestimates actual near-shore wind speed because, generally, two of the nearest four grid locations are over land (46). To calibrate the data to actual wind speed, we used data from the National Oceanic and Atmospheric Administration National Data Buoy Center to calculate the maximum daily wind speed at each port with a functioning weather buoy within 50 km. We compared buoy wind speeds to the reanalysis data wind speeds to determine the reanalysis wind speed that most closely approximates small craft advisory conditions, which are declared by the National Weather Service at wind speeds of greater than ∼11.2 m/s. We determined a reanalysis data wind speed of 7.5 m/s to be representative of this "high wind" condition (*SI Appendix*). We spot-checked historical small craft wind advisories (data that are not widely available), and found that days that were greater than 7.5 m/s according to the reanalysis data were often designated as small craft advisory conditions by the National Weather Service. As such, our high wind indicators may not correspond exactly to actual National Weather Service advisories but should be representative of weather conditions.

Empirical Approach. The data constitute a long unbalanced panel: daily fishing activity by nearly 500 vessels from 1994 to 2012. Because we have repeated observations on individuals, as well as a treatment group (the primary sector: the group that was exposed to the policy change) and a comparison group (the trip-limit sector: the group that was not exposed to the policy change), we can fully identify the effect of the management change on the average annual fishing rate in poor weather (as identified by a high wind day, defined in the previous section) using a difference-in-differences strategy with individual fixed effects (32). Nonexperimental research designs can be assessed by comparing pretreatment trends for the treatment and comparison group (47). This strategy relies on the assumption that in the absence of the policy change—the change to ITQs in the primary fishery—that the average annual fishing rate in poor weather in the primary fishery would have evolved similarly to the average annual fishing rate in poor weather in the trip limit fishery. Although the average fishing rate on high wind days was consistently higher in the primary fishery, the trends were similar (*SI Appendix*, Fig. S4 and Table S13). Because the gears, target species, and even many of the participants are the same, the two sectors are subject to similar unobserved shocks or trends. The inclusion of individual fixed effects eliminates bias from unobserved and unchanging vessel characteristics. Thus, a difference-in-differences specification with individual vessel fixed effects can precisely estimate the effect of the change in management regime (the treatment) on the annual proportion of fishing trips that occurred on high-wind days

$$R_{ift}|(w=1) = \beta_0 + \beta_1 Primary_f + \beta_2 PostITQ + \beta_3 (Primary_f \cdot PostITQ) + \mu_i + e_{ift}. \quad [2]$$

$R_{ift}|(w{=}1)$ is the annual average fishing rate (R_{ift}) for vessel i in each fishery f on high wind days ($w{=}1$). $Primary_f$ indicates the primary fishery (treatment group) vs. the trip-limit managed fishery. *PostITQ* indicates the years after individual quotas were institutionalized in the primary fishery. Thus, β_3 estimates the average treatment effect. The parameters $\boldsymbol{\mu_i}$ are individual fixed effects.

Fishermen make tradeoffs between risk and financial gain when they decide to start a fishing trip on a particular day. These tradeoffs are expected to change under catch share management. To quantify them, we model the daily fishing decision as a fixed effects logit model that accounts for time-invariant unobserved heterogeneity among vessels. The log-odds ratio for starting a fishing trip on day t is a linear function of expected revenue and weather in each management regime

$$\ln[P(F_{mit}=1|x_{mit},w_{mit},\alpha_i)]-\ln[1-P(F_{mit}=1|x_{mit},w_{mit},\alpha_i)]=\gamma r_{mit}+\delta w_{mit}+\alpha_i, \quad [3]$$

where $F_{mit}=1$ indicates vessel i took a trip on day t in management regime m. We define weather w_{mit} as a binary variable equal to 1 if there were high winds on day t in vessel i's port of potential departure. Expected revenue r_{mit} is estimated using observed prices and catches and was detailed above. The marginal rate of substitution (MRS) between risk and financial gain is $MRS = (\delta/\gamma)$, which gives the compensation (in dollars of expected revenue) that would be required for a fishermen to begin a fishing trip on a high winds day (33). Theoretically, the decision is a function of expected profit rather than revenue. However, cost data are not available, so we assume revenue and profits evolved similarly, a common assumption in fisheries economics research, where cost data are rare. We cannot observe nonfishery outcomes, so the model assumes that the latent net revenue of not fishing is constant over time.

Consolidation that occurred after the ITQ program (Table 2) could bias the results if there were systematic differences in the vessels that exited the fishery correlated with risk preferences. Vessels that exited tended to be smaller and were more likely to be based in California. We estimate Eq. **3** separately for vessels less than and greater than the median length (43 ft), for vessels that fished in California (which experienced significant effort reduction after the ITQ program) and those that fished in Oregon or Washington, and for vessels that exited the fishery after the ITQ and those that stayed. Dividing the sample into length categories allows the retention of the vessel fixed effects in each regression but will obscure the likely continuous nature of the effect of vessel length. Thus, we also estimate model 3 with a continuous interaction between vessel length and each independent variable, but excluding the vessel fixed effects (*SI Appendix*, Table S8).

In *SI Appendix* we report the results of several analyses that examine the identification assumptions (*SI Appendix*, Tables S13 and S14) and robustness of the estimates presented in the main article (*SI Appendix*, Tables S6–S12). The estimates pass the identification tests and were found to be extremely robust.

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