Income diversification and risk for fishermen

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Catches and prices from many fisheries exhibit high interannual variability, leading to variability in the income derived by fishery participants. The economic risk posed by this may be mitigated in some cases if individuals participate in several different fisheries, particularly if revenues from those fisheries are uncorrelated or vary asynchronously. We construct indices of gross income diversification from fisheries at the level of individual vessels and find that the income of the current fleet of vessels on the US West Coast and in Alaska is less diverse than at any point in the past 30 y. We also find a dome-shaped relationship between the variability of individuals' income and income diversification, which implies that a small amount of diversification does not reduce income risk but that higher levels of diversification can substantially reduce the variability of income from fishing. Moving from a single fishery strategy to a 50-25-25 split in revenues reduces the expected coefficient of variation of gross revenues between 24% and 65% for the vessels included in this study. The increasing access restrictions in many marine fisheries through license reductions and moratoriums have the potential to limit fishermen's ability to diversify their income risk across multiple fisheries. Catch share programs often result in consolidation initially and may reduce diversification. However, catch share programs also make it feasible for fishermen to build a portfolio of harvest privileges and potentially reduce their income risk. Therefore, catch share programs create both threats and opportunities for fishermen wishing to maintain diversified fishing strategies.

Fishing is a risky business. Not only do fishermen face the highest rate of work-related fatalities of any US industry, with a fatality rate more than 30 times higher than average (1), they face high financial risk as a result of high year-to-year variation in their income (2). In this article we focus on the latter form of risk. High annual variation in income is a problem that is common to a variety of occupations dependent on natural resources, and there has been extensive study of income risk-coping mechanisms, particularly for farmers in developing countries (3–10). Risk-reduction strategies used in agriculture might also be effective in fisheries. Crop diversification is a common means of reducing risk in agriculture, taking advantage of asynchronous variation in yield-response and prices to minimize idiosyncratic risk (11–13). Another common strategy in agriculture, particularly in semiarid regions with high fine-scale variation in rainfall, is to farm a number of geographically separated plots to ensure some will be in areas with sufficient rainfall (6). McCloskey (14) argues that risk reduction was the motivation of English farmers for "scattering each man's holdings in dozens of small strips" which, although inefficient, was widely practiced. Farmers can also plant a combination of crops adapted to wet or dry conditions to mitigate the risk associated with variable rainfall (15). A number of authors have argued that common property provides an important means of risk reduction that may be undermined by privatization (16–18). This literature relates primarily to grazing lands held in common to protect against the potential for spatial variation in rainfall. Variation in rainfall that would impact small private holdings is reduced for herders using a much larger area held in common. This advantage would, however, be undermined without some reasonably effective form of common property management to avoid overgrazing.

In the United States and many other developed countries, farmers have a number of risk-reduction mechanisms available to them beyond adopting less-risky farming strategies. They often have access to subsidized crop insurance, price supports, and futures markets (19–22), none of which are available to fishermen. Extending crop insurance-like programs to commercial fisheries harvesters has been suggested (23–26), but a feasibility study of a program for Bristol Bay Salmon in Alaska cast doubt on its viability. Although formal insurance programs do not exist, fishermen's fishing strategies may provide a means to reduce risk by diversifying their fishing activity across a variety of fisheries or areas (27–31). A growing literature suggests that fishermen or fishery managers should adopt portfolio approaches to manage species composition of catch to achieve the lowest variance in income for any level of expected return (2, 32–38). Data on vessels fishing off the West Coast (WC) and Alaska (AK) indicate that many, but by no means all, fishermen do diversify by participating in more than one fishery, and many fish in different areas, even moving between the WC and AK during the year.

Until fairly recently the ability to move between fisheries was largely unrestricted because access to most fisheries was relatively open. In the late 1970s, in response to growing concerns about overfishing and collapse of fish stocks, in the United States and many other countries, governments began to limit access to ocean fisheries. Initially limits on access were mainly geared toward phasing out access for foreign fleets, whereas domestic fishermen were given financial incentives such as loan guarantees and tax breaks to increase their participation in US fisheries (39). However, by the late 1980s (earlier for some fisheries) fishery managers began to limit access to fisheries by putting moratoriums on new licenses. In several cases licenses or vessels were bought back and retired to reduce fishing capacity (40–42), and in many cases, inactive or part-time fishermen were forced to forfeit licenses or were limited to small amounts of catch or very low productivity gear (e.g., hand reels).

More recently, "catch shares" have been allocated as individual transferable quotas or allocated to defined groups of vessels (e.g., harvest cooperatives), with strict but exclusive quotas specifying how much each individual or group can catch. Quota shares have generally been allocated at no cost to existing participants on the basis of catch history, but because most of the fisheries were overcapitalized before implementation of catch shares, there has often been consolidation, with some quota share holders selling or leasing catch shares to others and exiting the fishery (31). Although this consolidation would be expected to increase efficiency by lowering fixed costs and removing less-efficient fishermen, it may also tend to reduce the diversification both of those who exit the catch share fishery and those who remain.

These trends in limiting access to fisheries raise important questions about whether and how they have affected the ability of fishermen to diversify their fishing activity and whether and how reduced diversification affects variation in fishing revenues and consequently financial risk for fishermen. Because climate change and ocean acidification are expected to change the geographic range and relative productivity of individual fisheries and

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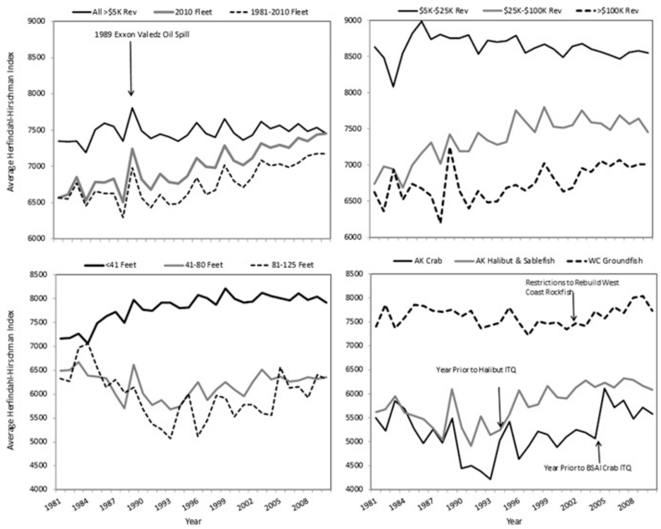

Fig. 1. Trends in average diversification for WC and AK fishing vessels with average annual revenue greater than $5,000 filtered by years involved in the fishery (*Upper Left*), by average gross revenues classes (*Upper Right*), by vessel length classes (*Lower Left*), and by involvement in specific fisheries before major management actions (*Lower Right*). The HHI declines from 10,000 when all revenues are derived from a single fishery toward zero as revenues are spread among more fisheries.

may increase volatility in productivity as well (43), the importance of diversification as a risk-reduction strategy may increase. We evaluate trends in diversification over time for vessels participating in fisheries in the US Extended Economic Zone (EEZ) off the WC and AK and analyze the relationship between diversification and variation in revenues at the vessel level. Our analysis confirms a decreasing trend in diversification over the last few decades and shows that diversification is correlated with a reduction in the variation of revenues.

Results

There are two main ways fishermen can diversify their fishing revenues: by targeting different species or species groups within a region and by fishing in different regions. We use a common diversification measure, the Herfindahl-Hirschman Index (HHI) (44, 45), also known as the Simpson diversity index (46), and calculate scores for individual vessels that indicate how diversified their fishing income was across species groups and regions each year. The HHI is an index of concentration whereby higher numbers correspond to increased concentration and therefore less diversification. The index takes a maximum value of 10,000 for an individual who derives revenues from a single species group and region and decreases toward zero as revenues are spread among more species and regions or spread more evenly among a given set of fisheries.

Average diversification of fishing revenues for WC and AK fishing vessels shows distinct but varying trends over time for different groups of vessels categorized by average revenue, length, and participation in specific fisheries (Fig. 1). The average HHI for all vessels in our sample exhibits no significant change or trend in diversification over time (Fig. 1, *Upper Left*). However, the average HHI for vessels that were still active in 2010, our most recent year of data, shows a significant trend of increasing concentration.* For the current fleet of vessels (2010 Fleet), revenue diversification is at the lowest level of any point in the past 30 y. Vessels that were fishing in 1981 and remain fishing in 2010 (1981–2010 Fleet) have also become less diversified but are still more diversified than the overall fleet that remains fishing in 2010. When considered in conjunction, these trends show that vessels that were less diversified were more likely to exit over time. Vessels that were in the fisheries in 1981 but had left before 2000 had an average HHI of 7,437 in 1981, whereas vessels that have remained in the fisheries from 1981 to 2010 had an average HHI of 6,565 in 1981. Those who entered more recently were initially and remain generally less diversified than those who were in the fishery in 1981 and remained through 2010, possibly because opportunities for diversification were more constrained for later entrants. There is a noticeable spike in concentration of fishing revenues in 1989, which is likely the result of disruptions from the Exxon Valdez oil spill in Prince William Sound, AK. Many vessels fished less in certain fisheries that year, although a large number earned income participating in clean-up efforts, income that we cannot account for in our diversification measure.

Average levels and trends of diversification differ for vessels with different levels of average revenues (Fig. 1, *Upper Right*). There is no significant trend in HHI for vessels with average income between $5,000 and $25,000. Vessels with average revenue between $25,000 and $100,000 tend to be more diversified than vessels with lower revenue, and there is a significant decrease in diversification (increase in HHI) of fishing revenue from 1981 to the late 1990s, and then a leveling off. Vessels with greater than $100,000 in average revenues are still more diversified on average but also exhibit a significant trend of decreasing diversification, particularly from 1991 onward.

Average levels and trends of diversification also vary with the size of vessels (Fig. 1, *Lower Left*). Smaller vessels (those less than 40 feet in length) tend to be less diversified than larger vessels. Diversification for smaller vessels has decreased (HHI increased) since 1980, although there is no significant trend. In contrast, diversification of medium-sized and large vessels increased between 1981 and the early 1990s but decreased over next two decades. Medium-sized and larger vessels are much more diversified than the smaller vessels, which is likely a result of the physical capacity of medium and large vessels to participate both in near-shore fisheries, such as salmon, as well as other fisheries further from shore. Larger vessels also have more ability to move between regions.

The increase in diversification of revenues (decrease in HHI) for these larger vessels through 1990 may be attributable in part to the "Americanization" of fisheries as foreign fishing vessels and joint ventures were phased out and were replaced by domestic vessels. Many fisheries also experienced shorter and shorter seasons over this period as the number of participants and fishing power increased and a "race for fish" ensued. To the extent they were able, larger vessels may have compensated for the shorter seasons by participating in more fisheries, but opportunities to move into new fisheries would have become rarer in the 1990s. By the mid 1990s, entry into new fisheries was no longer possible for most vessels because nearly all fisheries had moratoriums on entry, and many were beginning to reduce fleets through attrition, vessel buybacks, or catch share programs that allowed for voluntary exit and consolidation. After the mid-1990s even the larger vessels became less diversified (Fig. 1, *Lower Left*), although it is possible that changes in ownership structure (e.g., increases in multivessel ownership) could be masking diversification strategies that allow a single owner to diversify fishery income while individual vessels specialize.

For participants in some specific fisheries there were some distinct changes in diversification that followed major management actions (Fig. 1, *Lower Right*). Individual fishing quotas (IFQs) were implemented in the AK halibut and sablefish fisheries in 1995 and in the Bering Sea/Aleutian Islands AK crab fishery in 2005. In both cases, the year after the catch share program was implemented there was a jump in concentration for the vessels that had been involved in these fisheries. One-way t tests of mean HHI scores

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*We tested all trends shown in Fig. 1 for stationarity using Phillips-Perron unit-root tests and tested whether significant trends remain once the time series were differenced. The results, shown in Table S1, indicate stationary series with a deterministic time trend for the 2010 fleet, the 1981–2010 fleet, vessels with revenue between $25,000 and $100,000, vessels with mean revenue >$100,000, and the Alaskan Halibut fleet.

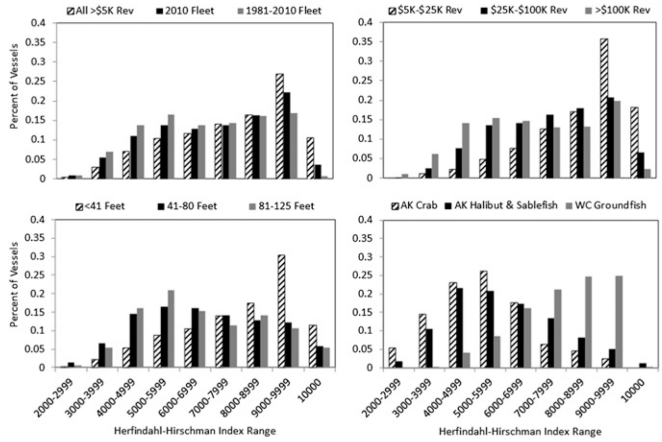

Fig. 2. Histograms showing percentage of vessels by ranges of HHI scores for WC and AK fishing vessels with average annual revenue greater than $5,000 filtered by years involved in the fishery (*Upper Left*), by average gross revenues classes (*Upper Right*), by vessel length classes (*Lower Left*), and by involvement in specific fisheries before major management actions (*Lower Right*). The HHI declines from 10,000 when all revenues are derived from a single fishery toward zero as revenues are spread among more fisheries.

before and after the AK crab and AK halibut and sablefish IFQ catch share programs reject the null hypothesis that the mean HHI was not higher in the post-catch share program years for both programs, suggesting that there was a significant reduction in diversification for the vessels that received quota in these two catch share programs. There is also an increase in HHI for participants in the WC groundfish fleet after introduction of more stringent catch and effort controls implemented to rebuild several overfished rockfish species and a vessel buyback program that was implemented in 2003. A catch share program was implemented in the WC groundfish fishery in 2011, but we do not yet have data to determine whether concentration increased at that point, and anecdotal evidence suggests the opposite may have been true.

There is wide variation in the degree of diversification across vessels within each class (Fig. 2). Although higher-earning and large vessels tend to be more diversified on average than smaller vessels and those with lower earnings, and participants in the AK crab and AK halibut and sablefish fisheries are more diversified than WC groundfish fishermen, all of these vessel classes include a wide range of HHI scores. This enables us to evaluate whether there is a relationship between diversification and the year-to-year variation in revenues for the individual vessels in our overall sample and for various subfleets.

We calculate the coefficient of variation, the ratio of the SD to the mean, of fishing revenues for each vessel over the years it appears in the data and compare this measure of income variability (as a proxy for financial risk) with the HHI score for the vessel averaged across years. Another potentially important measure of risk for fishermen is the ratio of the minimum revenues to mean revenues for a vessel. The "min/mean" ratio is a measure of the potential for a very bad outcome, which is likely important for many small owner-operator vessels. Results using this metric are included in *SI Results*. Because different vessels appear in the data for different time frames, we control for variation in income due to inflation by deflating annual income using the Bureau of Economic Analysis price index for personal consumption expenditures, using 2005 as the base year. Annual revenues for fishing vessels in our sample have an average coefficient of variation of 0.78. This variation results from a variety of factors, including variation in total catches and catch rates, variation in the prices fishermen receive for their catch, and variation in the amount of time they are able to fish due to regulations, weather, mechanical problems, etc.

If vessels are able to diversify into multiple fisheries whose revenues vary asynchronously, they should experience a reduction in volatility of revenues and thus risk (47). This is confirmed for all of our fleet groupings by estimating quadratic regressions of the coefficient of variation of gross fishery revenue (CV) as a function of HHI and HHI^2, although the strength and shape of the relationship varies across vessel groups (Fig. 3 and Table S2). With the exception of AK crab, all groups have a dome-shaped relationship between CV of revenues and HHI, such that small amounts of diversification are associated with an increase in the CV of revenues, but additional diversification (as measured by a lower HHI) lowers CV of vessel revenues at an increasing rate.[†] For some vessel groupings, including large vessels and participants in the AK crab and WC groundfish, CV declines with any significant level of diversification. The results from regressions of minimum over mean income against HHI show that the risk of having very low revenues relative to one's average revenues is also decreased by diversification (Fig. S2 and Table S3). These results are consistent both across vessels and within vessels, which we test by creating individual vessel panel datasets of differing duration and estimating the CV of gross revenues on diversification and diversification squared using individual vessel fixed effects (Table S4).

Because the meaning of various HHI scores in practical terms may not be readily apparent, we present the predicted CV of gross revenues for each of the vessel groupings using four hypothetical diversification schemes: no diversification (single fishery), a 90-10 split in revenues between two fisheries, a 50-50 split in revenues, and a 50-25-25 split in revenues between three fisheries (Table 1 and Fig. S3). Similar to the graphical results presented in Fig. 3, most vessel groupings show an increase in CV by moving from no diversification to a small amount (90-10 split) of diversification. The exceptions are the larger vessels and the participants in the AK crab and WC groundfish fisheries, for which predicted CV declines for even small amounts of diversification. As shown by the 50-50 split and 50-25-25 split, increasing diversification can offer substantial reductions in CV for all vessel groupings. Moving from a single fishery strategy to a 50-25-25 split in revenues reduces the CV of gross revenues between 24% and 65% for the vessel groups included in this study.

Discussion

Revenues from individual fisheries vary greatly year to year owing to natural variation in fish stocks and variation in price and the number of participants. Individual vessels experience additional variation as a result of differential fishing success. Diversification across multiple fisheries can reduce variation and the associated financial risk. It can also increase the minimum annual revenue relative to average revenue, which should reduce the risk of a business failure.

There are, however, a number of factors that may limit the feasibility or desirability of greater diversification, and there are factors other than regulatory change that may have driven fishermen to become more specialized. Technological change that increased technical efficiency over time may have both increased the need for consolidation and increased incentives to specialize, thereby driving decreases in diversification (48). Additionally, integration of global seafood markets may have tended to reduce asynchronous variation in prices (49), which would tend to weaken the risk reduction associated with diversification. Diversification could increase physical risk if it involves fishing in less-familiar areas or further from port. Diversification may also be costly. In many cases different fisheries require different gear that must be purchased, and there are often costs of acquiring licenses and, increasingly, quota. For some fishermen, the

[†]This dome-shaped relationship is not simply the result of an imposed functional form. It is visually apparent when looking at a scatter plot of the data and confirmed by a nonparametric kernel-weighted local polynomial smoothing regression, which provides a fit very similar to a quadratic regression (Fig. S1).

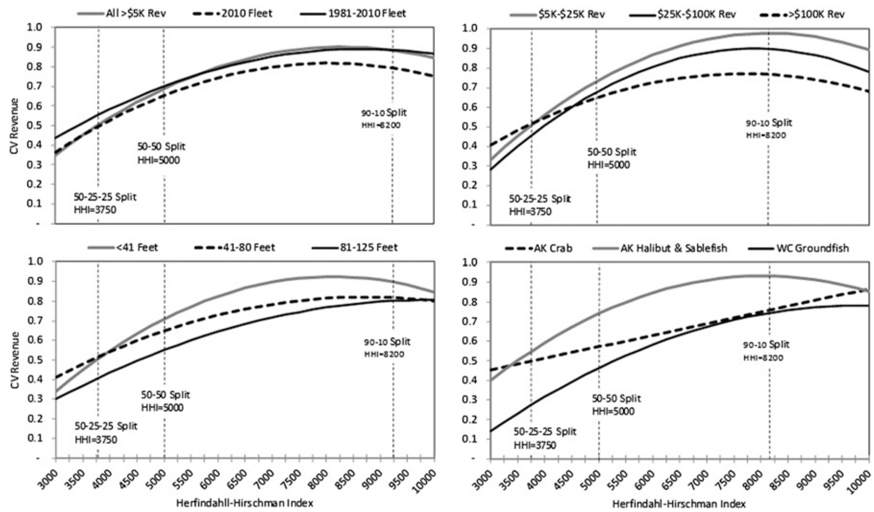

Fig. 3. Fitted relationships between the CV of gross revenues from fishing and HHI scores for WC and AK fishing vessels with average annual revenue greater than $5,000 filtered by years involved in the fishery (*Upper Left*), by average gross revenues classes (*Upper Right*), by vessel length classes (*Lower Left*), and by involvement in specific fisheries before major management actions (*Lower Right*). The HHI declines from 10,000 when all revenues are derived from a single fishery toward zero as revenues are spread among more fisheries.

variability in revenues is less important than the variability in costs, which may not be reduced by fishery diversification. It may also be the case that a vessel that can participate in several fisheries is not optimized for any specific fishery, and the captain and crew have less time to develop knowledge about any individual fishery. Consequently it may be less efficient than more-specialized vessels creating a tradeoff between average profitability and risk reduction. Although the potential tradeoff between risk reduction through diversification and efficiency loss has been noted in the literature (18, 29), it has not been documented and quantified empirically, and doing so would be an important extension of our research.

Some fishermen may diversify their income with nonfishing sources. Although the relationship is noisy, effort, measured in months with fishing activity, tends to move proportionately with total revenue, suggesting that in low-income years fishermen have more time to pursue income from some nonfishing source. Thus, total income variation may be much lower for those that have alternative income sources that are flexible, which would be a good risk coping strategy. However, it does not seem that, on average, fishermen respond to higher revenue rates (per month) by increasing the amount they fish. Nor do they increase effort when revenue rates are low, as we might expect if they were trying to achieve some target level of income. This may be because they are constrained by the season length and/or total allowable catch (TAC), although we can only hypothesize that at this point. Therefore, we do not believe excluding nonfishing income is a large limitation of this study because fishermen do not seem to be altering their fishing income risk reduction strategies in response to the condition of the fisheries.

Notwithstanding other factors that affect the propensity or desirability to diversify, the ability of fishermen to diversify fishery income may be limited (or facilitated) by management approaches and regulatory actions. Limited access programs, although clearly needed to constrain catches and increase economic efficiency in overcapitalized fisheries, may have reduced vessels' ability to manage risk by diversifying across fisheries and regions. As individual vessels are less able to fish in multiple fisheries and therefore reduce their risk, vessels may experience larger fluctuations in their income. This may increase the likelihood that small owner-operators will leave the fishery if they are less able to smooth their consumption over the bad years. This could lead to increasing corporate ownership of vessels if corporations are better able to manage large fluctuations in income or diversify by using multiple vessels in different fisheries.

Catch share programs have been shown to reduce the interannual variability of ecological indicators (50) and increase profitability of fisheries by increasing quality and value of catches, reducing costs, and increasing sustainability by improving control of total catch (51, 52). However, because catch shares are often introduced in fisheries that exhibit overcapacity, they often lead to consolidation and reduced diversification, which could increase income variability. Our results suggest that catch share programs for the AK crab and AK halibut and sablefish fisheries tended to reduce diversification. However, reduced diversification is not a foregone conclusion. Implementation of the catch share program in the WC groundfish trawl fishery in 2011 allowed many vessels to sit out the early part of the season and take advantage of high prices and catch rates in the pink shrimp and Dungeness crab fisheries, without any reduction in overall groundfish revenues. Catch share programs have the potential to allow vessels, with sufficient access to capital, to maintain or create their own portfolio of harvesting rights to mitigate risk of income variation if it is in the interest of an individual to do so (18). Additionally, because catch share programs tend to increase certainty about the share of catch a vessel is entitled to, vessels may be more able to use their licenses and quota as collateral for loans to smooth consumption during a bad year or to create their own portfolio of harvests by purchasing quota for different fisheries. The willingness of banks to allow catch share quota or other fishing rights to be used as collateral will likely increase over time as more catch share programs are adopted and banks become familiar with the industry, although it should be noted that catch share quota in the United States remain revocable privileges as opposed to clear property rights (53). Thus, the trend toward implementing catch share systems in fisheries creates both threats and opportunities for fishermen who wish to maintain diversified fishing strategies. Because in many cases consolidation is likely to lead to major efficiency gains, it may be inefficient to restrict it (e.g., by small aggregation limits or restrictions on what types of entities can own quota). However, it may be important to facilitate access to financing for operators that want to enter catch share fisheries to diversify their operations. Loan guarantees or direct financing programs may be useful and particularly important for small entities that face a higher cost of capital.

Our analysis clearly demonstrates that diversification of fishery revenues reduced variation in annual revenues on average and thereby provides a means for individual fishermen to reduce the high degree of financial risk. If reducing volatility of income and financial risk is a goal of fishery managers, they should consider the impacts of policies on the ability of fishermen to diversify. We are not suggesting that management actions that reduce diversification should be avoided. These actions may be necessary and prudent to ensure sustainability and increase economic efficiency. Furthermore, there may be other factors that motivate specialization and alternative strategies for reducing financial risk. However, when it is possible to limit or mitigate impacts of policies on diversification or to facilitate

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Table 1. Predicted CV of gross fishery revenue for HHI scores associated with alternative diversification schemes for groupings of WC and AK fishing vessels

	Predicted CV						
Vessel category	Single fishery	90-10 Split	50-50 Split	50-25-25 Split	Drop (%) single fishery to 50-25-25	Sample size	Mean revenue ($1,000)
All >$5,000 Revenue	0.84	0.90	0.69	0.49	41	30,757	155
2010 Fleet >$5,000	0.75	0.82	0.65	0.49	35	8,288	272
1981–2010 Fleet >$5,000	0.87	0.89	0.70	0.55	37	3,880	224
$5K-$25,000 Revenue	0.89	0.98	0.74	0.51	43	13,088	12
$25,000–$100,000 Revenue	0.78	0.90	0.68	0.46	42	10,081	56
>$100,000 Revenue	0.68	0.77	0.65	0.52	24	7,588	534
<40 Feet	0.85	0.93	0.71	0.50	41	24,628	49
40–80 Feet	0.80	0.82	0.65	0.51	36	5,184	221
80–125 Feet	0.81	0.78	0.51	0.40	50	600	1,047
AK crab	0.87	0.76	0.57	0.50	43	532	1,046
AK halibut and sablefish	0.85	0.93	0.74	0.55	36	3,327	224
WC groundfish	0.78	0.75	0.46	0.27	65	626	174

diversification, doing so may help to reduce financial risk for fishermen.

Methods

To measure diversification of a fishing vessel's gross revenues, we use the HHI, which is calculated by summing the squares of the percentages of gross annual revenues derived from groups of jointly targeted or managed species in each of four zones: Bering Sea/Aleutian Islands, Gulf of Alaska, Alaskan in-state waters, and the WC. We also consider less and more aggregated species groupings, but this species grouping had the strongest statistical relationship with income variation, and the results were qualitatively similar across groupings. The HHI is defined as:

$$H=\sum_{i=1}^{S_j}\sum_{j=1}^{4}p_{ij}^2, \quad \textbf{[1]}$$

where p_{ij} represents percentage (ranging from 0 to 100) of an individual's total gross revenues derived from species group i in region j.[‡] We define p_{ij} to be the percentage of a vessel's total annual gross revenue from 1 of 40 different species groupings in one of four regions—the Bering Sea/Aleutian Islands, Gulf of Alaska, Alaskan in-state waters, and the WC (Table 2). Not every species group is caught in each region, so there are a total of 84 total region-specific species groupings. The same species caught in different regions is considered a different species group because they generally come from different spawning stocks and ecosystems, and the permit or license required for access and the management methods vary. These differences may cause the returns from the resources to vary asynchronously and therefore could allow fishermen to reduce their risk by diversifying their fishing across these regions.

We work with a large dataset that includes annual landings and revenues between 1981 and 2010 by species, port, and vessel from all commercial fisheries in the US EEZ off the WC and AK. We present analysis based on 30,757 vessels for which we have vessel characteristics and at least 2 y of documented landings and revenues. We include only vessels with average annual revenues above $5,000 (adjusted to 2005 values), to exclude vessels not actively engaged in commercial fishing or for which fishing was not an important source of income. We also tried higher mean annual revenue cutoffs and generally had the same qualitative results. The number of years of observations per vessel varies from 2 to 30. The large dataset enables us to identify trends in diversification and relationships between diversification and variation in revenues, despite the relationship being noisy. However, the data also present a number of limitations. It would be preferable to use net income to measure diversification and compare it with risk, but cost data are not available for the vast majority of observations. Therefore, we are only able to explore diversification of gross fishery income. We have no data on nonfishery income and so are unable to explore risk-coping strategies that involve other sources of income. We are also unable to differentiate owners with multiple vessels, vessels with multiple owners, or changes in ownership over time, and we therefore treat each vessel as a single business entity over the period it appears in the data with the same vessel identifier.

To explore how diversification of fishery income affects year-to-year variation and thus financial risk, we estimate the statistical relationship between the CV of gross revenues for each vessel across years and their average HHI. Several authors suggest that there is a nonlinear relationship between risk and diversification (54, 55), and a nonparametric fitting of the data suggests a concave relationship between CV and HHI (Fig. S1). We therefore use a simple quadratic functional form and estimate the following linear regression model:

$$CV=\alpha_0+\alpha_1\overline{HHI}+\alpha_2\overline{HHI}^2+\varepsilon, \quad \textbf{[2]}$$

where CV represents the coefficient of variation of gross fishing revenues for each vessel, $\overline{HHI}$is the mean value of HHI for each vessel over the period it is included in the sample, and ϵ is a normally distributed error term with mean zero. Regression coefficients are reported in Table S2.

Table 2. Species groups used for calculating diversification indices

West Coast	Alaska
Pacific whiting	Pacific cod
Dover sole, thornyheads, sablefish	Flatfish
Rockfish and flatfish	Rockfish
Skate, dogfish, sharks	Atka mackerel
Pacific halibut	Pollock
California halibut, croaker	Other groundfish
Pink shrimp	Sablefish
Other prawns and shrimp	Pacific halibut
Crab	Herring
Salmon	Chinook salmon
Tuna	Sockeye salmon
Herring	Coho salmon
Coastal pelagics	Pink salmon
Echinoderms	Chum salmon
Other shellfish	Other salmon
Squid	Red king crab
Other species	Other king crab
	Opilio crab
	Other snow crab (Bairdi)
	Other crab
	Scallops
	Other shellfish
	Other species

[‡]We also calculated two other diversity indices: the Shannon Diversity index, also sometimes referred to as the entropy index, defined as: $H'=\sum_{i=1}^{S_j}\sum_{j}^{4}[p_{ij}\ln(p_{ij})]$, and a count of the number of fisheries a vessel has ever participated in. Although both alternative indices supported our conclusions and give qualitatively similar results, the HHI has a stronger statistical relationship with income variation than either alternative.

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