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Assessing diversification behavior of small-scale commercial fishers

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Abstract

Diversification within and outside of small-scale fisheries (SSF) is a common strategy to stabilize revenues and increase resilience following disturbances. Using SSF in Virginia, USA as a case study, Herfindahl–Hirschman Indices (HHIs) were used to characterize individual and fleet levels of income diversification, while generalized linear mixed models were used to examine drivers of diversification behavior. HHI income values indicate that fishers tended to exhibit specialized behavior. More diversified fishers tended to have less interannual revenue variability and higher annual incomes. Decisions to increase or decrease diversification were associated with various factors, including total years of participation, annual income, the type of licenses held, landings levels, participation in marine-related business outside of SSF, and market prices. An understanding of diversification levels and associated drivers of behavior can help fishery managers and governing entities predict how fishers will react to perturbations. Environmental changes that alter species distributions and increase the potential for invasive species, as well as shifting sociodemographics within the fishing industry, will likely continue to influence diversification behavior in the future. Developing strategies to reduce the impact of these events on fishers and fishing communities will help to increase resilience and reduce vulnerability in SSF.

Keywords: diversification; Herfindahl-Hirschman Index; small-scale fisheries; Virginia; resilience

Introduction

Commercial fishing is an inherently risky occupation, both financially and physically (Eckert *et al*. 2018, Lucas and Case 2018). Fishers face volatile markets, fluctuations in resource abundance, unpredictable weather conditions, and abrupt regulatory changes that influence participation on varying temporal and spatial scales, forcing fishers to make decisions under uncertainty. Decisions on where and how to fish, what to fish for, and whether or not to fish are further influenced by a number of ecological, social, and economic constraints (Yletyinen *et al*. 2018). Understanding factors influencing participation dynamics can be used to estimate impacts of adverse events to fishing communities and enhance resiliency (Fuller *et al*. 2017). Individual decision-making is likely heterogenous among fishers and fishing communities (Camerer 2000,Smith and Wilen 2005), and a one-size-fits all approach to fisheries management can increase the prevalence of unintended consequences and reduce adaptive capacity (Fulton *et al*. 2010). An enhanced understanding of the relationship that exists between small-scale fishers and drivers of participation, while complex, would provide a holistic characterization and is imperative for ecosystem-based management approaches (Marshall *et al*. 2018).

Small-scale fisheries (SSF) are considered particularly vulnerable to perturbations due to the inherent riskiness of fishing, limited access to financial capital, and rising social challenges, including competition with other user groups (e.g. coastal developers, recreational fisheries, and conservation groups), perceived injustices (e.g. socio-political underrepresentation), and increased government intervention (Flint and Luloff 2005, Bavinck *et al*. 2018). While broadly defined, SSF account for a substantial portion of the global commercial fishing population and are characterized as diverse and dynamic, often with strong social and economic dependence on fishing as a livelihood (Teh and Sumaila 2013, Basurto *et al*. 2017).

Sustainable livelihood strategies to increase resiliency and reduce vulnerability in SSF have been studied around the world (Panayotou 1985, Allison and Ellis 2001, Finkbeiner 2015, Selgrath *et al*. 2018). These strategies rely on an understanding of what motivates fishers to change participation by entering (exiting) various fisheries or sectors (e.g. marine-related or otherwise). Fishers can alter their participation through entry (exit) of the fishing industry itself or entry (exit) of specific fisheries while in the fishing industry. Reasons for entry (exit) have been noted in fisheries of varying scale with factors including residency, revenues and market conditions, historical productivity, resource abundance, and knowledge of the industry (Pálsson and Durrenberger 1982, Ward and Sutinen 1994, Pradhan and Leung 2004, Slater *et al*. 2013, Bucaram and Hearn 2014). The socio-cultural components of fishing (e.g. cultural significance, family and community support, job satisfaction, and occupational identity) can also influence decision-making, although they are often difficult to quantify. In some instances, socio-cultural factors can affect fishing decisions to a greater extent than economic or regulatory aspects and prevent fishers from exiting the industry even when there is no economic rationale to continue fishing (Marshall *et al*. 2007, Crosson 2015, Holland *et al*. 2020).

Small-scale fishers may diversify between fisheries or other employment to stabilize income, reduce vulnerability, and

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enhance long-term resiliency (Allison and Ellis 2001, Kasperski and Holland 2013, Sethi *et al.* 2014, Cline *et al.* 2017, Fuller *et al.* 2017, Nomura *et al.* 2022). Fishers can diversify within the commercial fishing industry by alternating fishing locations, seasons, gear types, or target species. Diversification within the industry can enable fishers to fish year-round rather than being restricted to specific times, areas, or seasons. Diversification can be considered a necessity due to environmental changes, which force fishers to switch between locations and species (Pinsky and Fogarty 2012, Papaioannou *et al.* 2021). Conversely, fishers with employment outside of SSF can choose to fish when conditions (e.g. resource abundance, ex-vessel price, etc.) are optimal and may recover more quickly following a disturbance (Beaudreau *et al.* 2019).

Despite the well-studied benefits of diversification, the behavior is not ubiquitous across fisheries (Kasperski and Holland 2013, Beaudreau *et al.* 2019, White and Scheld 2021). The ability to diversify can be constrained by lack of knowledge, management (e.g. limited entry, individual fishing quotas or IFQs), financial and social capital, and individual desire (Frawley *et al.* 2019). In the case of limited entry and IFQ programs, which are often introduced to rebuild overfished stocks, managers may face a tradeoff in terms of limiting diversification opportunities by imposing conservation measures. The size and condition of the fishery may also be important factors, as diversification decisions between small- and large-scale commercial fishers can differ in response to changes in stock status, market price, and management (Hentati-Sundberg *et al.* 2015, Yletyinen *et al.* 2018). Bockstael and Opaluch (1983) also noted that despite more profitable alternatives, fishers may continue in certain fisheries due to familiarity or risk aversion. The decision to specialize can be related to high investment or dependence on a fishery, as well as the condition of the fishery (i.e. high resource abundances and market prices may promote specialization; Allison and Ellis 2001, Kasperski and Holland 2013, Finkbeiner 2015). Nonetheless, specialization may constrain the capabilities of small-scale fishers and fishing communities to adapt during adverse events (Kluger *et al.* 2019). Acknowledging the extent to which diversification occurs may become more pertinent as ongoing environmental changes force fishers to switch between locations and species (Pinksy and Fogarty 2012, Dubik *et al.* 2018).

The individual decision-making processes related to participation and diversification in SSF are not well understood and represent a data need for fishery managers and regulatory entities. Although the drivers of entry (exit) decisions have been studied in some depth, a better understanding of how small-scale fishers are choosing to diversify (within and outside commercial fishing) on varying temporal scales would help reduce unintended consequences from management actions, including disruption of social and cultural norms, access issues, and non-compliance, as well as allowing for adaptation to changing environmental conditions (Degnbol and McCay 2007, Bennett and Dearden 2014, Stoll *et al.* 2016, Chambers and Carothers 2017). Utilizing Virginia's SSF as a case study, this research explored diversification levels and behaviors of small-scale commercial fishers through (i) assessing individual and fleet diversification using Herfindahl–Hirschman Indices (HHIs) and (ii) examining factors influencing individual diversification decision-making. This research contributes to a broader understanding of factors influencing participation and diversification decisions with implications to other SSF communities within and outside of the USA.

Methods

The Herfindahl–Hirschman Index (HHI), a measure of industry concentration commonly applied to fishing portfolio diversification, was used to explore levels of individual and fleet diversification (Miller 1982, Crosson 2011, Kasperski and Holland 2013, Finkbeiner 2015, Anderson *et al.* 2017). Individual decision-making models were subsequently constructed to expand on these characterizations and explore potential drivers of diversification behaviors.

Study system and data structure

The majority of SSF research is based in developing countries, although SSF also exists in developed countries such as the US (TBTI 2018). In the US Mid-Atlantic region, the state of Virginia is frequently recognized for its access to the Chesapeake Bay estuary and historically prominent SSFs that continue to contribute a significant portion to the state's total annual commercial landings through harvest of blue crab (*Callinectes sapidus*), eastern oyster (*Crassostrea virginica*), hard clam (*Mercenaria mercenaria*), striped bass (*Morone saxatilis*), Atlantic croaker (*Micropogonias undulates*), and other nearshore and inshore species by colloquially termed "watermen" (Kirkley 1997, McGoodwin 2001, Paolisso 2007). In the past two decades, however, the number of commercial fishing licenses sold in Virginia has declined >15%, while the number of senior licenses (≥65 years) has nearly doubled (White and Scheld 2021). These trends may portend broad societal impacts for coastal communities in the region, including a "graying of the fleet" and coincident shifts in resource dependence seen elsewhere that threaten the long-term resilience of SSF (Donkersloot and Carothers 2016, Cramer *et al.* 2018, Johnson and Mazur 2018).

The Virginia Marine Resources Commission (VMRC) oversees commercial landings, as well state licensing for commercial harvest, processing (i.e. shucking houses, crab shedding), fish dealers, charters operating in state waters, and aquaculture. A commercial registration license is required for all wild harvest, while additional licenses or permits are needed to participate in specific fisheries or sectors (e.g. aquaculture, chartering, seafood sales, and processing). In this work, two datasets maintained by VMRC—one for licenses and permits (hereafter, "licenses") and another for commercially licensed landings—were merged.

The license dataset included a unique individual license number and identified which licenses each individual held annually between 1993 and 2018. The initial year was omitted from analyses as many license types only existed in this year and were subsequently recategorized. Licenses were grouped into two broad categories, marine-related businesses and wild species fisheries, based on descriptions from the VMRC (http://www.mrc.virginia.gov/). Marine-related businesses included licenses related to commercial fishing, chartering, aquaculture, and seafood sales and processing (Table A1; $N = 30$ licenses and permits). Wild species fisheries requiring additional licenses for harvest were grouped based when available (Table A2; $N = 84$ licenses). Finfish was considered an aggregate category, as there are multiple species of finfish that

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can be harvested with a single gear type (e.g. gill net, fyke net, pound net) and do not require species-specific licenses (e.g. spotted seatrout *Cynoscion nebulosus*, Atlantic croaker *Micropogonias undulatus*). Licenses that did not include specific gear types were categorized by species (e.g. spiny dogfish, summer flounder). The resulting license dataset included the individual license number, year license was held, as well as the marine-related business and gear or species categories treated as binary variables with "1" representing that a license or permit was held for a given year and "0" indicating that the individual did not have the license.

The commercial landings dataset contained a unique individual license number, year of licensure, and for each year, indicated all landings by species, market grade, and gear, in terms of pounds and value from 1993 to 2018. The first year was omitted from analyses for consistency. Landings associated solely with aquaculture and landings from privately leased grounds were removed. Commercially landed species were aggregated across market grades and species with similar characteristics were also aggregated in some instances (Table A3). For example, various market grades (e.g. small, medium, and large) of bluefish (*Pomatomus saltatrix*) were grouped into one aggregate category, while alewife (*Alosa pseudoharengus*) and blueback herring (*A. aestivalis*) were grouped into a broader category for shads and herrings. Species with <100 landing observations in the dataset, cumulative across all market grades and years, were omitted as they were not considered viable diversification options.

These two datasets were merged such that each observation corresponded with an individual license number, year of licensure and included binary indicators of participation (holding a license) as well as volume and value of each species or species-aggregate landed in that year. A number of observations were removed: individuals with no landings and no commercial registration ($n = 17$), individuals with a commercial registration but no landings throughout the time series ($n = 2233$), and individuals with landings but no commercial registration ($n = 197$). These observations represent an aspect of the population where decision-making cannot be interpreted with available data (i.e. retaining licenses with no intention to use them, missing licenses). The merged dataset contained a total of 70 022 observations for 4890 licensed commercial fishers between 1994 and 2018 (Table A4).

Aggregate license categories (Table A2) were used to calculate the total number of licenses held by each individual in every year. For example, if an individual held a license for crab, oyster, and summer flounder in a particular year, then the individual would have a license count of three. Aggregate species categories (Table A3) were used to determine the total number of fisheries an individual participated in for a given year based on whether an individual had landings for that species or species aggregate. For example, if an individual had landings for any fishery considered "oyster" and any fishery considered "shad and herring," then the individual would have a species count of two (Table A3). The first and last year an individual held a commercial fishing license was used to calculate the total number of years an individual had participated in commercial fishing. Pearson correlation tests were used to evaluate the relationship between the number of licenses an individual held and year of entry as well as the total number of years an individual was present in the dataset. It was thought that individuals who entered the commercial fishing industry earlier and remained in the industry longer would be more diversified as a result of enhanced knowledge and capital, as well as decreased regulatory exclusion.

Herfindahl–Hirschman Indices

Individual species revenue and total annual incomes were adjusted for inflation using the Gross Domestic Product Implicit Price Deflator (USBEA 2022) and rescaled to thousands of USD in 2018 dollars.

HHI scores were calculated for each individual in every year using income across all species landed in a given year. HHI values are defined as

$$\mathrm{HHI}_{it} = \sum_{j=1}^{N} s_{ijt}^{2}, \tag{1}$$

where N is the total number of fisheries individual i could derive income from and s_{ijt} is the share of individual i's total income from fishery j in year t. HHI values range from 0 to 1, with higher values indicating that an individual is less diversified (i.e. more specialized participation). To evaluate differences across species, average HHI values for individuals with species-specific licenses were calculated. Spearman correlations were used to evaluate the relationship between HHI values, annual income, and income variability (i.e. coefficient of variation). Based on prior studies, it was expected that more diversified individuals would have less income variability though lower annual incomes (Sethi *et al.* 2014, Finkbeiner 2015).

Diversification model development

Generalized linear mixed models (GLMMs) were used to examine factors influencing individual diversification decisions. Decisions to increase or decrease diversification were modeled separately as the motivations for each may differ between individuals. For instance, individuals may be likely to enter a fishery if the expected returns are high, but unlikely to exit the same fishery when returns are low (Ward and Sutinen 1994). Diversification decisions were treated as binary and evaluated by a change in the number of licenses held between years. For example, when the response variable was the decision to increase diversification, a "1" represented an increase in the number of held licenses and a "0" indicated that the individual had no change in license holdings from one year to the next. Observations where an individual decreased the number of licenses held were not included in the increasing diversification model. When the decision to decrease diversification was assessed, a "1" represented a decrease in the number of held licenses and a "0" indicated no change. Correspondingly, observations where an individual increased the number of licenses held were not included in the decreasing diversification model. Individual diversification decisions were modeled based on observable conditions in the initial year to reduce the potential of endogeneity. For example, if an individual decreased the number of licenses held from 2006 to 2007, this decision would be modeled based on conditions observed in 2006.

Prior studies have related diversification behavior to the total number of years an individual has participated in commercial fishing, market conditions, individual landing revenues, regulation, as well as a number of ecological and socio-economic factors (Ward and Sutinen 1994, Bucaram and Hearn 2014, Hentati-Sundberg *et al.* 2015, Stoll *et al.*

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2016, Abbott *et al.* 2022). Model covariates considered here included: year as a continuous factor; individual annual income, volume of landings, and HHI value; holding licenses in marine-related businesses (in addition to commercial fishing); participation in niche (e.g. eel, horseshoe crab, whelk) or limited entry fisheries; total years of participation in the commercial fishing industry from 1994 up to that point in time; entry year; total number of species licenses held; holding a senior commercial fishing registration; and average market price received across all species landed in that year (see Table A5 for descriptive statistics of included variables). Furthermore, year was included as an interaction term on holding a license for a limited entry fishery to investigate how regulatory restrictions may change over time. Individual license numbers (i.e. individual fishers) were included as random effects in both models to control for unobserved heterogeneity in decision making. Variance inflation factors (VIF) were used to assess multicollinearity between covariates and VIF values of ≥5 were avoided (O'Brien 2007). Multiple models were constructed using various covariate combinations that were thought to have the greatest influence on diversification decisions. The final increasing and decreasing diversification models were selected based on Akaike's information criterion model comparison. All continuous covariates were standardized using *z*-score transformations. GLMMs were modeled as binomial regressions using a logit link and fit in the glmmTMB package for R Studio (Brooks *et al.* 2017). Odds ratios were calculated by exponentiating significant coefficient estimates. The change in odds was calculated by subtracting one from the exponentiated coefficient and multiplying by 100 to get a percentage.

Results

The average number of years a fisher held a license in the dataset was 17.53 ± 7.16 years. Fishers held 1.55 (±1.25) licenses and landed 1.73 (±2.60) species on average across all years (Table A6). On average across the time series, the proportion of fishers that changed the number of species specific licenses held from one year to the next in a given year was 41.2%, while 63.3% of fishers, on average, changed the number of species landed from one year to the next. The average inter-annual change in the number of licenses held and species landed across all individuals and years was slightly negative, although the standard deviations were large (Δ −0.003 ± 0.79 for licenses or permits held and Δ −0.046 ± 0.37 for species landed). The number of licenses held was positively correlated with the length of time an individual was present in the dataset (0.314, *P*-value < .001) and negatively correlated with the year an individual entered the dataset (–0.087, *P*-value < .001).

Herfindahl–Hirschman Indices

The average HHI value across all years and individuals was 0.82 (±0.24), indicating that most fishers are highly specialized (Tables A3; A7). Average HHI values for individuals with species-specific licenses across years suggest increased levels of diversification compared to the average individual (Figs 1 and 2). This is likely driven by blue crab being the dominant fishery in Virginia and individuals holding a license for this fishery being less diversified with average HHI values of 0.84 (Fig. 2b). Individuals holding a license for summer flounder (Fig. 1d) or clam (Fig. 2a) tended to be less diversified with average HHI values of 0.88 and 0.79, respectively. Individuals with an aggregate finfish license had an average HHI value of 0.73 across years (Fig. 1). However, when licenses for finfish are considered at the species level, HHI values are lower (Fig. 1). Individuals in niche fisheries (e.g. eel, horseshoe crab, whelk) tend to demonstrate higher levels of diversification with HHI income values between 0.66 and 0.76 (Fig. 1b, e, and f), while individuals with a license for spiny dogfish were the most diversified with average HHI income values of 0.57 (Fig. 1d).

There was a significant, positive correlation between average individual HHI values and the coefficient of variation, or income variability, for an individual across years in the time series (0.145, *P*-value < .001). This indicates that less diversified fishers tend to have increased variability in annual income, as expected. Correlation between average individual HHI values across years and average total annual income was negative and significant (−0.235, *P*-value < .001), indicating that more diversified individuals tended to have higher annual incomes on average.

Diversification models

Increasing diversification models

The GLMM for individual decision-making to increase diversification included 58 452 observations of 4890 commercial fishers. Of these observations, 9458 (~16%) were instances of increasing diversification. The final covariates included in the increasing diversification model are shown in Table A8 with corresponding odds ratios in Table 1.

The total years a fisher was in the dataset (i.e. held a commercial fishing license) had a negative impact on the decision to increase diversification in the following year (*P*-value < .001). The odds of increasing diversification decreased by 3% with a one standard deviation increase in years of participation in the commercial fishing industry (odds ratio, OR = 0.97). Annual income derived from commercial fishing had a positive impact on the decision to increase diversification, meaning individuals with higher incomes (from commercial fishing) were more likely to diversify in the next year (*P*-value < .001). While significant, the odds of an individual increasing diversification from an increase in annual income in the prior year are considerably low, likely driven by a small number of highly diversified, high income individuals (OR = 1.000004). The impact of whether an individual had any landings on increasing diversification was negative (*P*-value < .001), with the odds of obtaining an additional license decreasing by 20% if an individual had no landings in the previous year (OR = 0.80). The decision to not land, especially in consecutive years, is likely reflective of exit from a particular fishery or the industry altogether. Similarly, holding a senior commercial fishing registration had a negative and significant impact on the decision to increase diversification (*P*-value < .001), with the odds of an individual increasing diversification declining by 41% the following year if holding a senior commercial fishing registration (OR = 0.59). When total licenses for wild harvest are considered, there is a negative impact on increasing diversification in the next year (*P*-value < .001), and the odds of increasing diversification decline by 31% with a one standard deviation increase in the number of licenses held (OR = 0.69). The impact

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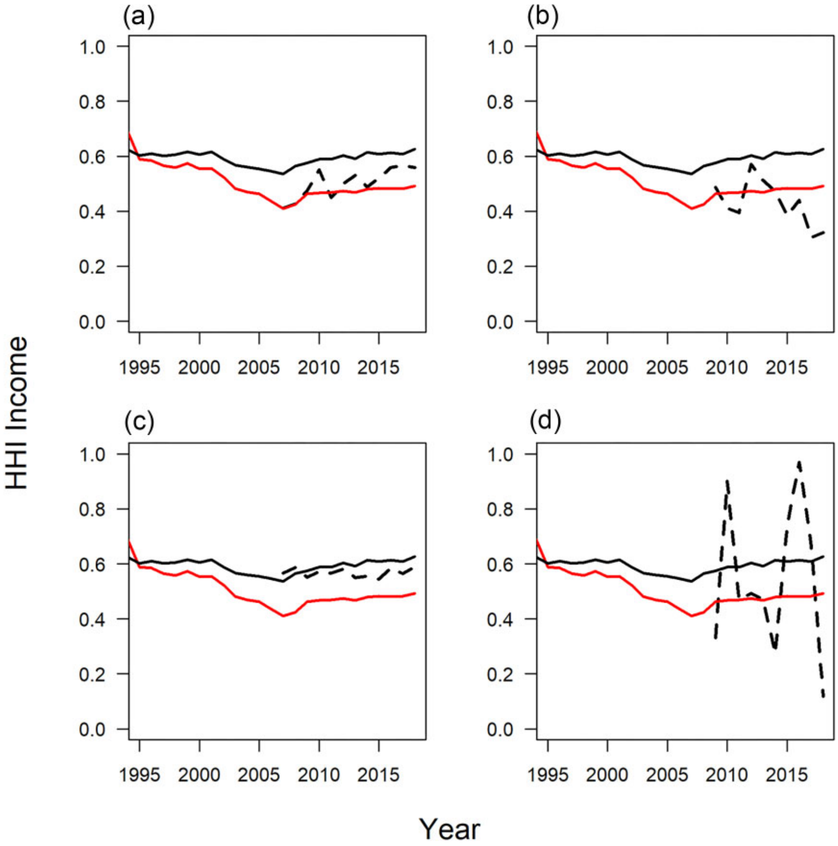

Figure 1. Average HHI values across individuals holding a license in an aggregate wild finfish fishery (solid black line) or species-specific finfish fisheries (dashed black line) compared to the average HHI income values across all individuals in the commercial fishing industry, including fisheries where species-specific licenses are not required (red line) between 1994 and 2018. Top row, left to right: (a) black drum, (b) black sea bass, (c) striped bass, and (d) summer flounder.

of holding a license for a marine-related business outside of commercial fishing (chartering, aquaculture, or seafood sales and processing) on the decision to increase diversification was positive and significant. The odds that an individual would increase diversification in the following year increased 26% if an individual held a license for a marine-related business outside of commercial fishing. Similarly, if an individual held a license for a limited entry fishery, the odds of increasing diversification in the following year increased by 12% (P-value < 0.01; OR = 1.12).

Decreasing diversification models

The GLMM for individual decision-making to decrease diversification included 60 474 observations of 4890 commercial fishers. Of these observations, 11 570 (~19%) were instances of decreasing diversification. The final covariates included in the decreasing diversification model are shown in Table A9 with corresponding odds ratios in Table 2.

The total number of years an individual held a commercial fishing license negatively impacted the decision to decrease diversification (P-value $< .001$). For a one standard deviation increase in the years of participation in the commercial fishing industry, the odds of an individual decreasing diversification decreased by 3%. Annual income also had a negative impact on the decision to decrease diversification the following year (P-value $< .001$); however, the odds of an individual decreasing diversification with higher incomes are negligible. When an individual had no landings across any species in the previous year, the odds of decreasing the number of licenses held increased by 94%, all else equal (P-value $< .001$; OR = 1.94). Individuals holding a license for a limited entry fishery were more likely to decrease diversification in the following year (P-value $< .001$); however, when year is included as an interaction term on participation in limited entry fishery, the impact on decreasing diversification is negative (P-value $< .001$). This suggests that individuals holding a license for a limited entry fishery are likely to decrease diversification initially, but across time this effect is reduced or even reversed (P-value $< .001$; OR = 0.98). Participation in marine-related businesses had a negative impact on decreasing diversification (P-value $< .001$) with the odds of removing a license decreasing by 35% when an individual participates in a marine-related business outside of commercial fishing (OR = 0.65). The number of wild harvest licenses held had a positive impact on the decision to decrease diversification (P-value < 0.001), with the odds of an individual decreasing diversification given a one standard deviation increase in the number of licenses held increasing by 163% (OR = 2.63). Individuals with more licenses may be unable to further diversify as they have already capitalized on available fisheries and, therefore, the only option is to maintain these licenses or decrease diversification. Holding a senior commercial fishing registration (≥65 years) had a positive impact on the decision to decrease diversification (P-value $< .001$), with the odds of an individual decreasing diversification when having a senior commercial fishing license increasing by 33.8% (OR = 1.34). The effect of average market price on the decision to decrease diversification was positive (P-value $< .001$) with a one standard deviation increase in

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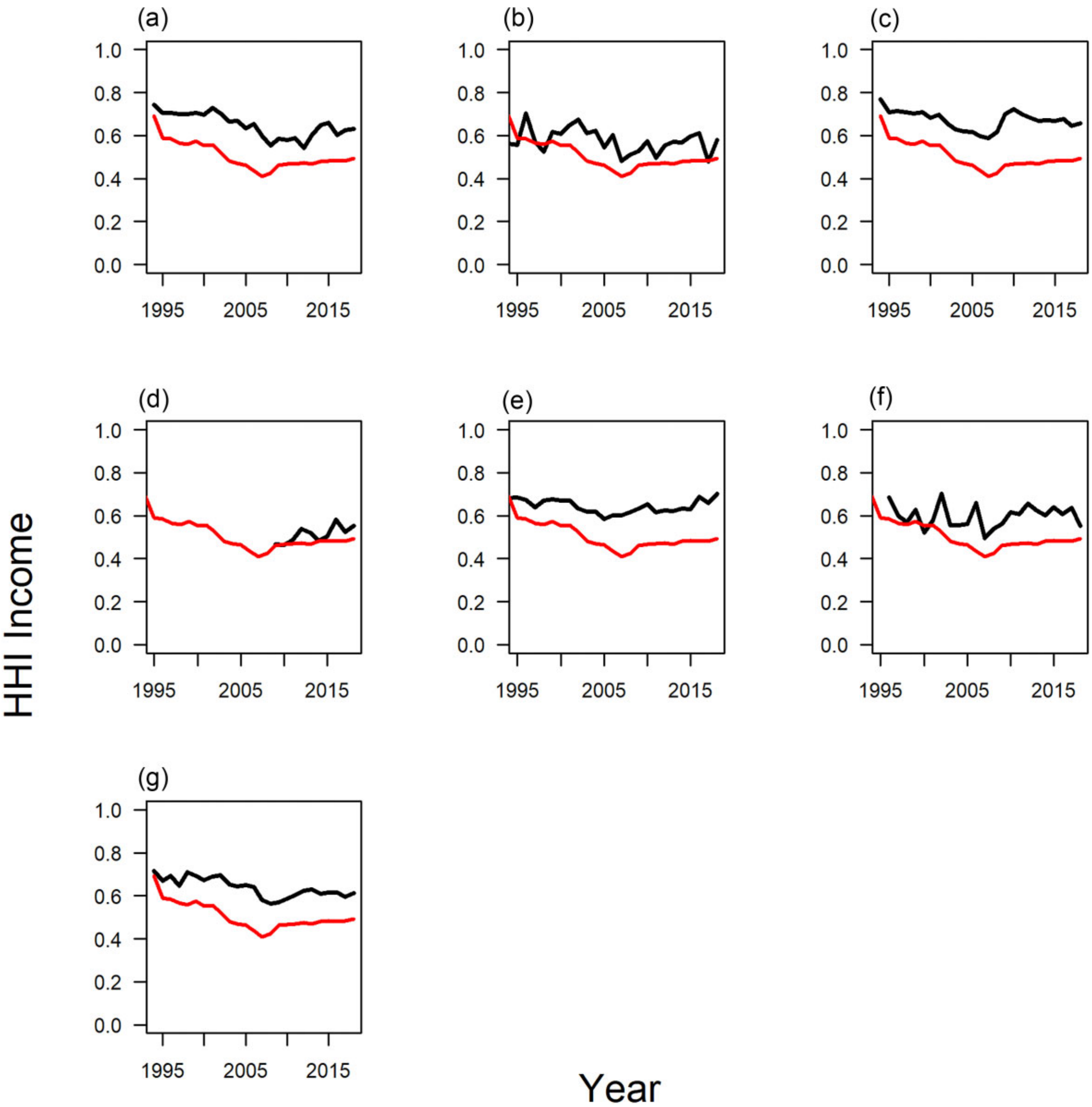

Figure 2. Average HHI values across individuals holding a license for species-specific fisheries (black line) and the average HHI income values across all individuals in the commercial fishing industry, including fisheries where species-specific licenses or permits are not required (red line) between 1994 and 2018. Top row, left to right: (a) clam, (b) conch, (c) crab, (d) dogfish, (e) eel, (f) horseshoe crab, and (g) oyster.

market price (±\$1.94) resulting in a 4% increase in the odds that an individual will remove licenses in the following year (OR = 1.04).

Synthesis and predictions

Individual predictions for both diversification models indicate that in a given year, the average probability of an individual increasing diversification is 15.7% (± 9%), while the average probability of decreasing diversification is 18.7% (± 15%) (Fig. 3).

Based on the differences in variances explained by individual random effects in both models, there is evidence that individual heterogeneity is a more important factor influencing the decision to increase diversification as opposed to decrease diversification (Tables A8 and A9). There were similar negative effects on increasing and decreasing diversification decisions based on the number of years an individual participated in commercial fishing. The more years an individual is in the industry, the more likely one is to remain unchanged in the number of licenses held and diversification behavior stabilizes. Thus, length of participation in the commercial fishing industry may serve as a barrier to diversification and potentially limit the adaptive capacity of fishers and fishing communities. Alternatively, other factors seemed to promote changes in fishing behavior with opposite effects on the decision to increase or decrease diversification. Fishers that had no landings in the previous year, held a senior commercial registration, received higher average market prices, or held more licenses, were less likely to increase and more likely to decrease diversification. These factors may be drivers of declines in participation and low levels of diversification observed presently. Higher annual incomes and holding a license for a marine-related business, however, may promote industry growth and fishers with these characteristics were more likely to increase and less likely to decrease diversification. Fishers holding a license for a limited entry fishery were more likely to increase and decrease diversification, however, these effects are not constant over time.

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Table 1. Odds ratios and probabilities calculated from model estimates, standard errors, and associated *P*-values of covariates on the decision to increase diversification.

	Increasing diversification		
Predictors	Odds ratios	Std. error	*P*
Total years	0.97	0.00	<.001***
Annual income	1.00[a]	0.00	<.001***
No landings	0.80	0.03	<.001***
Marine business	1.26	0.05	<.001***
Senior registration	0.59	0.03	<.001***
Permit count	0.69	0.01	<.001***
Average market price	1.01	0.01	.48
Limited entry	1.12	0.05	<.009**
Year	1.00	0.00	.22
Limited entry*year	1.00	0.00	.45
Random effects			
σ^2	3.29		
τ_{00}	0.72		
ICC	0.18		
$N_{\text{VMRC.ID}}$	4890		
Observations	58 452		
Marginal R^2/conditional R^2	0.057/0.225		

Significance codes: "***" <.001, "**" <.01, "*" <.05, "blank" > .05.
[a]The odds ratio for "annual income" is rounded to the nearest hundredth for consistency, although it is significant (*P*-value < .001) at 1.000004.

Table 2. Odds ratios and probabilities calculated from model estimates, standard errors, and associated *P*-values of covariates on the decision to decrease diversification.

	Decreasing diversification		
Predictors	Odds ratios	Std. error	*P*
Total years	0.97	0.00	<.001***
Annual income	1.00	0.00	<.001***
No landings	1.94	0.07	<.001***
Marine business	0.65	0.02	<.001***
Senior registration	1.34	0.06	<.001***
Permit count	2.63	0.04	<.001***
Average market price	1.04	0.01	<.001***
Limited entry	1.51	0.06	<.001***
Year	0.99	0.00	.01*
Limited entry*year	0.98	0.00	<.001***
Random effects			
σ^2	3.29		
τ_{00}	0.54		
ICC	0.14		
$N_{\text{VMRC.ID}}$	4890		
Observations	60 474		
Marginal R^2/conditional R^2	0.227/0.336		

Significance codes: "***" <0.001, "**" <0.01, "*" <0.05, "blank" > 0.05.

Discussion

Despite the suggested benefits of diversification (Kasperski and Holland 2013, Anderson *et al.* 2017, Holland *et al.* 2017), this research finds that not all fishers in Virginia are actively diversified in SSF and thus, might have limited adaptive capacity to respond to perturbations. Average indices of income diversification suggest that a significant portion of Virginia's fishers are deriving income and landings from one or two species. This corroborates the findings of White and Scheld (2021), which indicate less than half of commercial fishers are diversified between species, although these studies consider license holdings differently. These levels of diversification are likely driven by the dominant blue crab fishery as individuals with a license for blue crab tend to be less diversified, possibly due to the financial investment or because many fishers in this fishery participate on a part-time basis. Nonetheless, this is similar to findings of US West Coast and Alaskan fisheries where specialization is becoming increasingly common (Holland and Kasperski 2016, Ward *et al.* 2018, Beaudreau *et al.* 2019). While the relationship between increased diversification and decreased income variability in Virginia's SSF is similar to other US fisheries (Kasperski and Holland 2013, Sethi *et al.* 2014, Anderson *et al.* 2017), evidence indicates that specialization may be an important adaptive strategy of fishers to increase income during favorable conditions (e.g. increased market price, high species abundance) (Finkbeiner 2015, Anderson *et al.* 2017, Ward *et al.* 2018). This research finds that HHI is negatively correlated with annual incomes, meaning that more diversified individuals tend to have higher annual incomes or, alternatively, that individuals with higher annual incomes to be more diversified. It is possible that fishers with lower annual incomes and decreasing diversification decisions may be tied to exit from the industry or indicate participation in outside employment that serves as the primary source of income.

Due to the financial cost and difficulty of obtaining licenses to enter many commercial fisheries in Virginia, particularly licenses for limited entry or quota-managed fisheries, it is possible that individuals add these licenses with no intent to utilize them other than retaining them for potential opportunities or later resale. These individuals remain specialized in certain fisheries despite expanding their license portfolio (White 2023). Individuals with higher annual incomes may also be more resource dependent on commercial fishing (i.e. full-time fishers) and, ultimately, have an enhanced ability or need to expand their fishing portfolio.

Differences in diversification levels based on license holdings for specific species are also apparent. On average, individuals with a license for blue crab are less diversified and individuals holding a license for spiny dogfish are more diversified. The reasoning for specialization in the Virginia blue crab fishery is unclear, although it could be due to the demands of obtaining a limited entry license for the fishery, the amount of capital investment for gear (e.g. crab pots, pot puller), or the potential for high market values (and thus, revenues) in a given year. It is also plausible that this particular fishery is predominantly comprised of part-time fishers that solely target blue crab and have additional sources of income outside of commercial fishing. Higher levels of diversification for individuals with licenses for various finfish species are not unexpected, as gears used in these fisheries can be used to target a wide variety of commercially profitable species (e.g. gill nets, pound nets). Nonetheless, the ability to diversify using less selective gear types remains limited by the scope of the licenses that a fisher holds.

This research finds that some individual characteristics are related to changes in diversification, while others generate stability and potentially lessen the adaptive capacity of fishers. The odds of increasing or decreasing diversification with changes in annual income were negligible in this study, indicating that large changes in annual income may be needed for individuals to increase or decrease diversification. This

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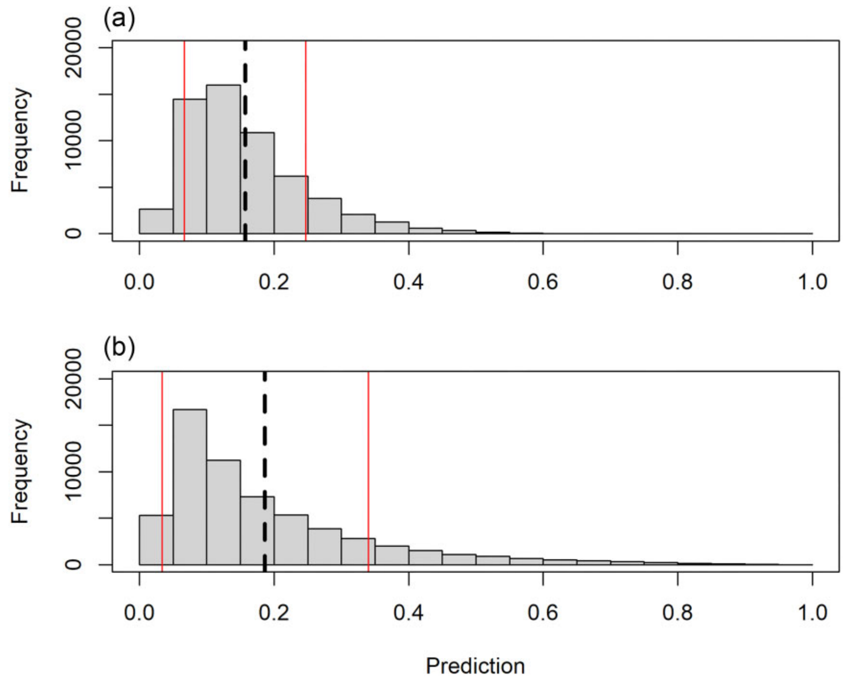

Figure 3. Probability of individuals increasing diversification (a) or decreasing diversification (b) in a given year, including the averages across all individuals and years (dashed line) and standard deviation (solid lines).

finding is likely driven by a few individuals with high annual incomes (>$200 000) holding nearly double the average number of licenses compared to the broader commercial fishing population. This research also finds that diversification decisions within SSF can vary based on existing license holdings. For example, the probability that an individual would choose to decrease diversification is significantly impacted when an individual holds a senior commercial registration. This "graying of the fleet" phenomenon corresponds with shifts in resource dependence and decreased resilience, as older fishers reduce participation (or exit in some cases) and there is limited new entry for the transfer of generational knowledge and social memory (Folke 2006, Donkersloot and Carothers 2016, Cramer *et al.* 2018, Johnson and Mazur 2018).

The length of time an individual was present in the dataset was positively correlated with the number of licenses held (i.e. more diversified). Individuals that remain in the industry longer may have the knowledge, financial capital, and ability to diversify more readily than a newcomer, though this is in contrast to the findings that indicate holding a senior license or more permits lessen the odds of increasing diversification behavior (Ward and Sutinen 1994, Holland and Kasperski 2016). However, similar to findings of Abbott *et al.* (2022), as the cumulative years of participation increases, an individual is less likely to continue diversifying. This may be due to the fact that the fisher already holds a desired number of licenses, or it is not feasible to enter another permitted fishery. Cumulative years of participation also had a negative effect impact on the decision to decrease diversification. These findings suggest that the longer a fisher remains in the commercial fishing industry, the less likely they are to alter their participation behavior (e.g. increase or decrease diversification). Both models, however, indicate differing impacts of age (i.e. holding a senior commercial registration) and thus, should be considered separately from years of participation or experience.

As more fisheries require additional licenses and management trends toward private property regimes, the ability to diversify may become increasingly constrained (Holland and Kasperski 2016, Stoll *et al.* 2016, Silver and Stoll 2019). Although a viable tool to reduce overfishing (Parslow 2010), limited entry and individual fishing quotas have been found to negatively impact revenues and job security of individuals without sufficient quota in the US West Coast (Carothers 2013, Holland and Kasperski 2016). Furthermore, these management regimes can promote specialization as individuals with larger quotas can attribute more time and effort to the fishery (Carothers 2013, Holland and Kasperski 2016). It has been shown, however, that privatized management regimes reduce the need for income diversification as harvest and fishery revenues stabilize and, thus, serve as a risk reduction strategy (Essington *et al.* 2012, Kroetz *et al.* 2015). In addition to the impacts on established fishers, the cost of limited entry or quota fisheries may prevent new fishers from participating, especially younger individuals (Chambers and Carothers 2017). The cost, as well as requirements of maintaining a limited license or quota share, can reduce the adaptive capacity of fishers in alternating between periods of diversification and specialization. Crosson (2011) suggests that these management strategies overlook the socio-cultural aspects (i.e. generational ties, community structure) of commercial fishing. Fishers that have historically switched between species, gears, and locations to compensate for environmental and economic changes (e.g. low species abundance, low market price) may be displaced under limited entry and quota programs. This study finds that fishers holding a license in a limited entry fishery had a 2% reduction in the odds of decreasing diversification in the following year, although it is possible that fishers are retaining licenses as a "just in case" risk management strategy.

In addition to the economic and social influences on diversification decisions, ongoing environmental changes have the

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ability to further constrain or enhance diversification opportunities. Fishers may be able to adapt to these environmental changes by following the northward shift in species distributions (Lucey and Nye 2010, Pinsky and Fogarty 2012) or diversifying into other established or emerging fisheries. Birkenbach and Smith (2022) and Papaioannou *et al.* (2021) indicate that fishers tend to be habitual in their fishing locations, however, and there is likely individual heterogeneity in the decision to switch between fishing locations. If fishers choose to follow distributional shifts, it is probable that increased travel time and cost, as well as infrastructure and management will become constraining factors. Nonetheless, fishers are often acutely aware of changes within fisheries and can utilize traditional knowledge and experiences to adapt to shifts in various ways (Papaioannou *et al.* 2021), including the exploitation of emerging or invasive species. In Virginia, opportunities to capitalize on emerging and invasive species fisheries are presented with the expansion of the invasive blue catfish (*Ictalurus furcatus*) and probable climate-induced range shift of white shrimp (*Litopenaeus setiferus)* (White 2023). These emerging fisheries can enhance economic opportunities for small-scale fishers, although they may be met with varying management and social responses (Dubik *et al.* 2018).

Diversification decisions are not limited to within the commercial fishing industry and the ability to diversify between commercial fishing and other occupations can also be influenced by economic, environmental, and social factors. Fishers who hold licenses for marine-related businesses, in addition to commercial fishing, are still vulnerable to abrupt environmental and economic changes as each income source pulls from similar sources of marine productivity (Hanh and Boonstra 2018). For example, the seafood sales and processing sector is closely intertwined with SSF and thus, both can be negatively impacted by management changes such as fishery closures or declines in species abundances. However, holding a license for marine-related business had a positive impact on the decision to increase diversification and a negative impact on the decision to decrease diversification. Each marine-related business considered in these analyses has had notable shifts in participation since the mid-1990s. Participation in aquaculture has increased with the rapid growth of the intensive oyster aquaculture sector, while seafood sales and processing participation have continuously declined with the consolidation of fish houses and processing plants. While there is limited diversification into marine-related businesses by individuals holding a commercial fishing license, employment outside of SSF, whether marine-related or otherwise, is a viable option for many fishers (White and Scheld 2021, White 2023).

Conclusions

This research assessed levels of diversification and drivers of diversification behavior within the commercial fishing industry using Virginia as a case study; however, it is possible that additional factors, have an effect on the ability to diversify (Abbott *et al.* 2022). Social and cultural factors were not accounted for in these analyses, but likely play a significant role in decision-making (Marshall *et al.* 2007). The use of individual random effects in both diversification models control for these additional factors, but do not provide insight as to how they may drive decision-making. Likewise, levels of diversification outside of SSF are likely greater than noted as this study was limited to participation in aquaculture, chartering, and seafood sales and processing. Fishers may also derive income from other sources to counteract variability in commercial fishing and thus, may participate in fewer fisheries or remain limited to fishing in a particular season (White 2023). This study did not consider harvest from private leases (extensive aquaculture) or participation in federally managed fisheries, although both are an option of diversification for many fishers and likely contribute to annual income. Future research may expand on the drivers of various participation and diversification behaviors in SSF through direct conversations with fishers or a survey instrument (White 2023).

An enhanced understanding of the factors that influence participation and diversification can help managers assess, and potentially lessen, the impacts of adverse events on fishers and fishing communities. The findings of this study indicate that there are opportunities to increase the resilience of fishers and fishing communities through an understanding of various factors that determine whether the decision to diversify or specialize is optimal in reducing financial vulnerability. Furthermore, levels of diversification can have varying impacts on fishery resources and result in unintended socio-ecological consequences if not well understood. Predicting diversification decisions based on specific license holdings can be used to counter the graying of the fleet through an understanding of resource dependence and participation characteristics. As a socio-cultural norm, it is common for older fishers to continue commercial fishing past what is considered retirement age, although in limited capacity (White *et al.* 2023, *under review*). As the average age of fishers continues to increase, the need to promote new entry into the commercial industry as a means of continual workforce development is imminent, especially in terms of transferring generational knowledge.

Individual diversification decisions of small-scale commercial fishers are influenced by a number of variables, some of which cannot be quantitatively captured or identified presently. The decision to diversify within and outside of SSF is likely heterogenous and based on imperfect information of economic and environmental conditions. These broad, annual decisions are likely the cumulation of daily, or even shorter temporal scale, decision-making. While this study analyzed decision-making of commercial fishers in terms of license holdings in Virginia, it is probable that similar variables may impact decision-making in other fishing communities with comparable characteristics. An enhanced understanding of levels of diversification, as well as the drivers behind diversification decisions in SSF, can help to strengthen the adaptive capacity of inherently vulnerable communities by developing mechanisms that reduce the impacts of adverse economic, environmental, and social events.

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Author contribution

Both S.B.W. and A.M.S. were involved in the conceptualization, data curation, investigation, and formal analysis. S.B.W. constructed the original draft of the manuscript with review

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and editing from A.M.S. A.M.S. conducted data validation and supervised the development of this manuscript.

Supplementary material

The following supplementary material is available at ICESJMS online—licensing/permitting and species categories, license/permit counts for each species and marine-related industries, descriptive statistics of model covariates, average and standard deviation of the total licenses/permits an individual held or species landed and changes in the total licenses/permits, descriptive statistics for Herfindahl–Hirschman Indices by year, and GLMM model outputs for increasing and decreasing diversification.

Conflict of interest

No potential competing interest was reported by the authors.

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Data availability

The data underlying this article cannot be shared publicly for the privacy of individual identification and landings data. Data were retrieved from the Virginia Marine Resources Commission in Fort Monroe, Virginia.

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