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Harmful Algal Blooms: Identifying Effective Adaptive Actions Used in Fishery-Dependent Communities in Response to a Protracted Event

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The "blob" of anomalously warm surface water that persisted in the North Pacific Ocean from 2013 to 2016 resulted in a massive harmful algal bloom (HAB) of *Pseudo-nitzschia* along the entire United States West Coast. The bloom produced record-breaking concentrations of domoic acid, a marine neurotoxin, that contaminated seafood and necessitated fisheries harvest closures beginning in May 2015. The subsequent closures were unprecedented in length and geographic extent, generating an economic shock for fishing communities. We sought to identify effective adaptive actions used in fishery-dependent communities in response to this event. Using survey data collected across 16 fishing communities following the 2015 HAB event, we empirically identified factors affecting an individual's: (1) absolute magnitude of income loss, (2) likelihood of income loss recovery, and (3) severity of emotional stress. Our findings indicate that individuals who suffered greater absolute income losses were exposed to longer fisheries closures, more dependent on shellfish as a source of income, and employed in the fishing industry. Income diversification was an effective strategy for reducing and/or recovering HAB related income losses. Advertising was also found to be an effective income recovery strategy, but for fishers it was associated with increased emotional stress. If increasing the adaptive capacity of fishery-dependent coastal communities to HAB events is a policy goal, then costs to adaptive action such as emotional stress, limited access to alternate fisheries, new fishing gear, a lack of alternate job skills or access to job networks, and a lack of advertising know-how will need to be addressed.

Keywords: harmful algal bloom, economic impacts, emotional stress, resilience, cultural ecosystem services, fishery-dependent communities, *Pseudo-nitzschia*, domoic acid

INTRODUCTION

Phytoplankton blooms are natural phenomena that sustain marine ecosystems, but some phytoplankton species produce toxic or otherwise negative impacts on human health and wellbeing (Berdalet et al., 2015). When this occurs, the blooms are called harmful algal blooms (HABs). These HABs are an increasing concern for fishery-dependent coastal communities. The occurrence and intensity of HABs are increasing, a trend that is expected to continue with ongoing changes in global ocean conditions, including warming and acidification (Berdalet et al., 2015; McCabe et al., 2016; Zhu et al., 2017). Coastal fishing communities that rely on the marine environment for their livelihood and wellbeing may be severely affected by worsening HABs (Millennium Ecosystem Assessment Program, 2005; Fleming et al., 2014; United Nations Environment Programme, 2017).

Impacts from HABs include human illness through biotoxin exposure, recreational and commercial fishery closures due to seafood contamination, associated revenue losses in business, a loss in seafood provisioning, and beach cleanup costs (Hoagland et al., 2002; Bauer, 2006; Moore et al., 2008; Dyson and Huppert, 2010; Anderson and Plummer, 2016). HABs can also undermine non-material/cultural ecosystem services such as opportunities for spiritual enrichment and engagement in traditional activities (Millennium Ecosystem Assessment Program, 2005; Bauer, 2006; Willis et al., 2018). These non-material benefits are important to human wellbeing, providing a sense of place and identity in coastal communities (Ritzman et al., 2018; Willis et al., 2018). Livelihood insecurity and lost cultural opportunities can impact the physical and emotional health of individuals with increased levels of stress, anxiety, depression, and substance abuse (Nurse et al., 2010; Cunsolo Willox et al., 2013; King et al., 2015; Clayton et al., 2017). Additionally, impacts to emotional health can cause concern for public health due to associated increases in anti-social behaviors such as aggression and violence (Clayton et al., 2017; Hayes et al., 2018).

There is a growing recognition of the importance of economic and social impact assessments of HABs (Jewett et al., 2008; Backer, 2009; Bauer et al., 2010; Berdalet et al., 2015). Efforts thus far have primarily documented aggregated economic losses (Anderson et al., 2000; Hoagland et al., 2002; Jin et al., 2008; Dyson and Huppert, 2010). Research on human experiences of HAB events is starting to emerge (Ritzman et al., 2018; Willis et al., 2018). These studies provide valuable insights into the breadth of HAB impacts. However, the literature lacks information linking the severity of impacts experienced by an individual to sociodemographic factors and adaptive actions pursued. The impacts of changing environmental conditions or natural disasters such as HABs depend on the extent to which an individual is exposed to adverse conditions (exposure), the degree to which the individual depends on affected resources (sensitivity), and the individual's capacity to adapt to the changes experienced (adaptive capacity) (Adger, 2006; Cinner et al., 2018). The adaptive capacities required, and adaptive actions taken in HAB-affected communities are likely to be similar to those that follow any closure or disruption to a community's life and livelihood. However, predictable and unpredictable closures have different psychological impacts and require different adaptive responses. In seasonally closed fisheries, strategies to adapt to seasonally varying income will have been developed; this may include seasonal migration, maintaining multiple occupations or income-streams (e.g., Allison and Ellis, 2001). Similar adaptations occur in any natural resource-based livelihood system subject to variability, such as rain-fed farming or the fisheries of upwelling zones. HAB-induced closures are, however, more like the disruptions that occur following extreme climate events, geological hazards or oil spills. Communities with strong political, social, and financial capitals tend to fare better immediately following disasters, enabling longer-term processes of transformation or recovery (Himes-Cornell et al., 2018). HABs are disaster events and require disaster preparedness and response strategies. If they become the "new normal" then longer-term adaptive responses will be needed, such as diversifying out of fishing and coastal tourism related to shellfish harvesting and consumption or relocating to more economically viable areas.

An individual's adaptive capacity depends on the ability to comprehend the changing conditions, access assets (e.g., financial, technological, and service), connect to social support networks, and pursue an alternate livelihood (Cinner et al., 2018). Inherent to adaptive capacity are the costs associated with adaptive actions. For example, an individual may pursue an alternate livelihood or move to a new area, but the emotional cost associated with the loss of occupational and place identity may limit flexibility in this regard (Marshall et al., 2012; Cinner et al., 2018; Willis et al., 2018). Similarly, the costs associated with pursuing alternate fishing strategies, such as new gear or entry limitations, may be prohibitive for an individual lacking access to sufficient assets (Cinner et al., 2018). To identify effective adaptive actions and inform policy development, a mechanistic understanding of an individual's vulnerability to a HAB event is needed. We aim to fill this research gap using survey data collected across 16 fishing communities on the United States West Coast following the massive 2015 HAB of *Pseudo-nitzschia*. In particular, we empirically identify factors affecting an individual's: (1) magnitude of income loss, (2) likelihood of income loss recovery, and (3) severity of emotional stress.

2015 UNITED STATES WEST COAST HAB EVENT

The "blob" of anomalously warm surface water that persisted in the North Pacific Ocean from 2014 to 2016 resulted in a massive HAB of *Pseudo-nitzschia* that occurred along the entire United States West Coast (Bond et al., 2015; McCabe et al., 2016). The bloom produced record-breaking concentrations of domoic acid that accumulated in shellfish. Consumption of contaminated shellfish may cause amnesic shellfish poisoning in humans, an illness that can result in serious neurological damage including permanent short-term memory loss.

Beginning in May 2015, the exceedance of regulatory action limits for domoic acid concentrations necessitated fisheries closures that lasted into 2016. The closures were unprecedented in both duration and geographic extent (Moore et al., 2019). Commercial Dungeness crab fishers lost over 10% of the 2015–2016 fishing season in Washington and Oregon and up to 72% of the season in California (Moore et al., 2019). The commercial Dungeness crab fishery is vital to the health of coastal fishing communities on the United States West Coast because it generates the highest revenues and has a high rate of vessel participation (Fuller et al., 2017). Revenue from the fishery declined by \$97.5 million compared to the previous season (National Marine Fisheries Service, 2016), generating an economic shock for fishing communities and resulting in fisheries resource disaster declarations for the California Dungeness crab fishery and the Quileute Tribe (Washington) Dungeness crab fishery.

In addition to the closures of the Dungeness crab fishery, many areas were also impacted by closures to recreational razor clam harvesting. Tourism related to the recreational razor clam fishery is an important source of income to some coastal communities, particularly in Washington and Oregon (Hoagland et al., 2002), and participating in this recreational activity is an important cultural tradition among both indigenous and settler populations in the Pacific Northwest (Bauer, 2006). Beaches in northern Oregon lost 77% of the 2015 razor clam season while areas in Washington lost up to 66% (Moore et al., 2019).

TABLE 1 | Fishing communities targeted by the survey.

State	Community	HAB index[1]	Proportion of Dungeness crab catch within community[2] (%)	Proportion of Dungeness crab catch coast-wide[2] (%)
Washington	Grays Harbor	0.12	31	17
	Baker's Bay	0.12	7	4
Oregon	Astoria	0.13	2	21
	Garibaldi	0.13	59	0.2
	Newport	0.13	4	15
	Winchester Bay	0.13	31	0.2
	Coos Bay	0.13	9	5
	Port Orford	0.13	51	0.2
	Brookings	0.13	20	1
California	Crescent City	0.72	42	2
	Arcata Bay	0.72	26	2
	Fort Bragg	0.72	12	1
	Bodega Bay	0.58	73	1
	Half Moon Bay	0.58	14	2
	Monterey	0.58	0.01	4
	Morro Bay	0.20	6	1

[1]The HAB index measures the proportion of the commercial Dungeness crab fishing season lost due to the HAB-induced closures. Data source: Moore et al. (2019). [2]The proportion of Dungeness crab catch within a community and coast-wide, respectively provide the percentage of the commercial fish catch (by revenue) that was attributable to Dungeness crab for that region and the total coast-wide Dungeness crab revenues attributable to that port averaged from 2011 to 2015. Data source: Pacific Fisheries Information Network.

DATA AND METHODS

Survey Data

To assess the impacts of the 2015 HAB event, we draw on primary survey data collected across 16 pre-identified fishing communities on the United States West Coast (**Table 1**; Moore et al., submitted). The focus communities included important fishing ports for the United States West Coast that are expected to be particularly vulnerable to a HAB event (Moore et al., 2019). The survey aimed to provide a holistic view of HAB impacts to individuals and their communities with questions on social, cultural and economic outcomes. Solicited responses included information on income losses, emotional stress, and the impact on family gatherings, holidays, or traditions. Data on coping strategies, adaptive actions, and sociodemographic factors were also captured. The survey instrument was deemed IRB (Internal Review Board) exempt by the University of Washington Human Subjects Division and deployed in the summer of 2017 using a mixed-mode design. A mail survey was sent to individuals identified as working in either the shellfish industry or hospitality related businesses. Hospitality providers were included in the survey because we recognize that the recreational harvest and consumption of shellfish are activities that motivate tourist visits to the coast. When these activities are unavailable due to HAB-induced closures, tourist visits to hotels and restaurants in coastal fishing towns decrease (Dyson and Huppert, 2010). This occurs even in coastal towns where shellfishing is uncommon (Ritzman et al., 2018). In addition to the mail survey, an online version was advertised via shellfish-related state agency listservs with participants self-selecting into the survey. Further details on the survey design, implementation, and response rates can be found in the **Supplementary Materials**.

Our analysis is limited to a subsample of survey respondents who: (1) lived in one of the 16 focal communities, (2) were primarily employed in either the fisheries or hospitality industries, and (3) indicated experiencing a financial loss due to the 2015 HAB event. The subsample comprises 262 responses, 61% of which were submitted through the online survey. There were 106 respondents from California communities (40%), 54 (21%) from Oregon, and 102 (40%) from Washington. The respondents were predominantly men (75%). White/Caucasians were the majority ethnic group (70%) followed by Black/African Americans (9%), Asians (8%) and American Indian/Native Alaskans (5%). Summary statistics for the variables we use in our empirical models are given in the following paragraphs. The statistics are largely similar to those reported for the full data set by Moore et al. (submitted).

Commercial fishers constituted 64% of respondents (**Table 2**). More than half the fishers indicated that their primary occupation was as a fishing license owner and/or vessel operator. The remaining fishers were employed as deckhands (8%), fish processors (15%), or in fish-related retail (25%). Almost all of the survey respondents employed in the hospitality industry indicated that they were either the manager (55%) or owner (44%) of a store, restaurant or hotel. Only one survey respondent indicated being a hospitality employee.

TABLE 2 | Number of survey respondents by occupation.

	N	Fisheries (%)	Hospitality (%)	Total (%)
Fisheries				
Fish owner/operator	87	51.79		33.21
Deckhand	14	8.33		5.34
Fish processor	25	14.88		9.54
Fish-related retail	42	25.00		16.03
Hospitality				
Store/Restaurant/Hotel owner	41		43.61	15.65
Store/Restaurant/Hotel manager	52		55.32	19.86
Store/Restaurant/Hotel employee	1		1.06	0.38
Total (*N*)		168	94	262

Approximately a third of the survey participants relied on shellfish for three-quarters or more of their income (**Table 3**). Fishers indicated higher levels of shellfish dependence than individuals employed in hospitality. Over 70% of hospitality providers earned up to half their income from other sources compared to only 38% of fishers. Fishers were more likely to earn more than hospitality providers. Although the median income for both groups fell within the medium income bracket ($50,000–$99,999) (See **Supplementary Table A1** for all variable definitions), only 11% of hospitality providers achieved a high income bracket (>$100,000) compared to 28% of fishers (**Table 3**).

Over 40% of survey respondents reported experiencing high income losses (>$9,999) due to the HAB event (**Table 3**). Commercial fishers bore most of these losses. While more than half of fishers experienced high income losses, most individuals employed in hospitality reported low income losses (<$3,000).

TABLE 3 | Summary of socioeconomic variables by employment industry.

	Fisheries (%)	Hospitality (%)	Total (%)
Income loss bracket			
Low (<$3,000)	16.67	60.64	32.44
Medium ($3,000–$9,999)	27.38	22.34	25.57
High (>$10,000)	55.95	17.02	41.98
Shellfish income			
<25%	10.71	37.23	20.23
25–49%	26.79	35.11	29.77
50–74%	25.60	9.57	19.85
>74%	36.90	18.09	30.15
Income bracket			
Low (<$50,000)	25.60	37.23	29.77
Medium ($50,000–$99,999)	41.67	51.06	45.04
High (>$100,000)	27.98	10.64	21.76
Income recovery			
Yes	25.60	50.00	34.35
Emotional stress			
Strongly agreed	38.10	28.72	34.73
Cultural impact			
Strongly agreed	39.36	28.57	32.44

The proportion of income an individual lost due to the HAB event could not be calculated from the survey data because the brackets for an individual's typical income and their income loss were too broad.

More than 80% of survey respondents took adaptive or coping actions to deal with income losses. Adaptive actions (e.g., gaining alternate employment) have the potential to reduce and/or recover income losses while coping actions (e.g., borrowing) provide only temporary relief. The actions most commonly taken across all survey respondents were borrowing (39%), advertising (27%), alternate fishing (21%), and trading/bartering (20%) (**Table 4**). Hospitality providers were most likely to engage in advertising (55%) and borrowing (47%) while fishers were most likely to borrow (35%) and engage in alternate fishing (24%). It is notable that 15% of hospitality providers also reported engaging in alternate fishing strategies. This may reflect that some hospitality providers fish as a secondary source of income or food supplement. In adopting adaptive actions, HAB-associated income losses were recovered by half of the hospitality providers and just over a quarter of the fishers (**Table 3**).

Over a third of the survey respondents strongly agreed that they had experienced stress as a result of the HAB event (**Table 3**). Interviews conducted in 2 of the 16 communities prior to the survey indicated that stress was often due to financial insecurity and associated increases in relational strain (Ritzman et al., 2018). Commercial fishers indicated slightly higher levels of stress with 38% inclined to strongly agree relative to 29% of hospitality providers. Similarly, almost a third of survey respondents strongly agreed that their family gatherings, holidays, or traditions were negatively impacted by the HAB event (henceforth termed cultural impact) due to a lack of shellfish to eat. Examples of these cultural impacts include an inability to partake in traditional gift-giving of shellfish, a lack of crab for holiday meals, and disruption to social activities – notably razor clam harvests – that are integral to community identity (Ritzman et al., 2018). Fishers reported somewhat greater cultural impacts than hospitality providers (39% of fishers strongly agreed compared to 29% of hospitality providers; **Table 3**).

TABLE 4 | Adaptive and coping actions taken in response to the 2015 HAB event by employment industry.

	N	Fisheries (%)	Hospitality (%)	Total (%)
Adaptive actions				
Alternate job	40	17.26	11.70	15.27
Alternate fishing	54	23.81	14.89	20.61
Advertising	72	11.90	55.32	27.48
Trade/Barter	53	10.71	37.23	20.23
Discounts	34	14.88	9.57	12.98
Coping actions				
Borrowing	102	34.52	46.81	38.93
Government assistance	29	10.12	12.77	11.07
Default	32	14.88	7.45	12.21
Total (*N*)		168	94	262

HAB Index

The extent to which an individual was exposed to adverse conditions resulting from the 2015 HAB event was quantified using an index (henceforth referred to as the HAB index) of lost fishing opportunities (Moore et al., 2019). The index measured the proportion of the commercial Dungeness crab fishing season lost due to the HAB closures. This measure compensates for regional differences in season lengths, start and end dates and conservation closures. In Washington and Oregon, commercial Dungeness crab fishers in surveyed communities lost 12 and 13% of the 2015–2016 fishing season, respectively, while in California, lost fishing opportunities ranged from 20 to 72% of the season (**Table 1**).

Model Specifications

To assess the influence of sociodemographic factors and adaptive actions on the severity of HAB impacts experienced by an individual, empirical models were developed using the survey data. In particular, models were developed to understand the factors affecting an individual's (1) magnitude of income loss, (2) likelihood of income loss recovery, and (3) the severity of emotional stress. Two model specifications were developed for each of these impacts – one based on all the survey respondents and the other for commercial fishers only. The separate model for commercial fishers included industry specific variables and aimed to distinguish effects for this population. A similar model for hospitality providers was not developed due to limited sample size (Long and Freese, 2014). Definitions for all model variables are provided in **Supplementary Table A1**.

Income Loss

The following ordered logit regression model was used to estimate the probability of income loss magnitude:

$$\Pr(\text{Income loss bracket} = \mathrm{m}|\mathbf{x}) = \Lambda(\tau_{\mathrm{m}} - \mathbf{x\beta}) - \Lambda(\tau_{\mathrm{m}-1} - \mathbf{x\beta}) \quad \text{for m} = 1-3,$$

where:

$$\text{Income loss bracket} = \begin{cases} \text{Low} & \text{if m} = 1 \\ \text{Medium} & \text{if m} = 2 \\ \text{High} & \text{if m} = 3 \end{cases}$$

Λ is the logistic cumulative distribution function for a random error ϵ with mean of 0 and $\mathrm{Var}(\epsilon) = \Pi^2/3$, τ_1 through $\tau_{\mathrm{m}-1}$ are cut-points (thresholds) that are estimated by the model,
and across all survey respondents:

$$\mathbf{x\beta} = \beta_1 \textit{HAB Index} + \beta_2 \textit{Fisheries Job} + \beta_3 \textit{HAB Index} \times \textit{Fisheries Job} + \beta_4 \textit{Shellfish Income} + \beta_5 \textit{Income Bracket} + \beta_6 \textit{Business Owner},$$

while for fishers only:

$$\mathbf{x\beta} = \beta_1 \textit{HAB Index} + \beta_2 \textit{Fisheries Job Type} + \beta_3 \textit{Shellfish Income} + \beta_4 \textit{Income Bracket}.$$

We expect the level of absolute income loss to rise with increased exposure to the 2015 HAB event, as measured by higher values of the HAB index. Fishers are expected to have higher levels of income loss relative to hospitality providers in the event of a HAB, because their incomes are directly tied to closed fisheries. Additionally, HAB exposure, as measured by the HAB index, is expected to differentially impact fishers. Therefore, our model includes an interaction term to capture these differential effects. A greater income dependence on shellfish is expected to increase the level of income loss, but an individual's income bracket may have opposing effects. A higher typical income entails greater potential losses, but likely also increased assets that can be drawn upon to mitigate losses (Cinner et al., 2018). All else the same, employees are expected to experience higher income losses than business owners because we suspect that they may lose their jobs first if employers suffer ongoing losses (Ritzman et al., 2018). Finally, the model for fishers includes a variable for fisheries job type. This variable also controls for business ownership because among the fishing jobs only fishing license owner/operators are classified as business owners. We hypothesize that fishing license owner/operators may have experienced greater income losses than fish processors and fish retailers if reduced market prices for Dungeness crab were passed onto fishing license owner/operators. However, we expect that fishing license owner/operators may have experienced lower income losses than deckhands for the same reason we expect employees to fare worse than business owners.

Income Recovery

The probability of income loss recovery was estimated using the following logit regression model:

$$\Pr(\text{Income recovery} = 1|\mathbf{x}) = \Lambda(\mathbf{x\beta})$$

where:

$$\text{Income recovery} = \begin{cases} 1, & \text{if income losses were fully recovered} \\ 0, & \text{otherwise} \end{cases}$$

Λ is defined as above, and across all survey respondents:

$$\mathbf{x\beta} = \beta_0 + \beta_1 \textit{Income Loss Bracket} + \beta_2 \textit{Income Bracket} + \beta_3 \textit{Fishing Job} + \beta_4 \textit{Business Owner} + \beta_5 \textit{Alternate Fishing} + \beta_6 \textit{Alternate Job} + \beta_7 \textit{Advertising},$$

while for fishers only:

$$\mathbf{x\beta} = \beta_0 + \beta_1 \textit{Income Loss Bracket} + \beta_2 \textit{Income Bracket} + \beta_3 \textit{Fishing Job Type} + \beta_4 \textit{Alternate Fishing} + \beta_5 \textit{Alternate Job} + \beta_6 \textit{Advertising}.$$

Higher levels of income loss are expected to decrease the likelihood of income recovery. On the contrary, the likelihood of income recovery is expected to increase with a higher income bracket because a higher typical income is likely to be associated with greater access to assets that can be drawn upon to mitigate losses (Cinner et al., 2018). All else the same, we hypothesize that hospitality providers are more likely to recover income losses than fishers because they may more easily substitute their business income. For example, hospitality providers could target non-shellfish related tourist activities. Fishers on the other hand may face access restrictions and lack the gear necessary to substitute fishing activities (Holland and Kasperski, 2016). Similarly, amongst fishery jobs, we suspect that fishing license owner/operators are least likely to have recovered income losses since they may have waited for the fishery to open rather than obtain a substitute income source. Finally, adaptive actions (alternate fishing activities, taking a side job, and advertising business more widely) are all expected to increase the likelihood of income recovery.

Emotional Stress

The probability of strongly agreeing to experiencing emotional stress was estimated using the following logit regression model:

$$\Pr(\text{Emotional stress} = 1|\mathbf{x}) = \Lambda(\mathbf{x}\boldsymbol{\beta})$$

where:

$$\text{Emotional stress} = \begin{cases} 1, & \text{if strongly agreed} \\ 0, & \text{otherwise} \end{cases}$$

Λ is defined as above, and across all survey respondents:

$$\begin{aligned} \mathbf{x}\boldsymbol{\beta} = \beta_0 \; + \; & \beta_1 \mathit{Income\ Loss\ Bracket} + \beta_2 \mathit{Income\ Recovery} \\ & + \beta_3 \mathit{Income\ Bracket} + \beta_4 \mathit{Cultural\ Impact} \\ & + \beta_5 \mathit{Alternate\ Fishing} + \beta_6 \mathit{Alternate\ Job} + \beta_7 \mathit{Advertising} \\ & + \beta_8 \mathit{Trade/Barter} + \beta_9 \mathit{Discounts} + \beta_{10} \mathit{Borrow} \\ & + \beta_{11} \mathit{Assistance} + \beta_{12} \mathit{Default}, \end{aligned}$$

while for fishers only:

$$\begin{aligned} \mathbf{x}\boldsymbol{\beta} = \beta_0 \; + \; & \beta_1 \mathit{Income\ Loss\ Bracket} + \beta_2 \mathit{Income\ Recovery} \\ & + \beta_3 \mathit{Income\ Bracket} + \beta_4 \mathit{Cultural\ Impact} \\ & + \beta_5 \mathit{Alternate\ Fishing} + \beta_6 \mathit{Alternate\ Job} + \beta_7 \mathit{Advertising} \\ & + \beta_8 \mathit{Trade/Barter} + \beta_9 \mathit{Discounts} + \beta_{10} \mathit{Borrow} \\ & + \beta_{11} \mathit{Assistance} + \beta_{12} \mathit{Default}. \end{aligned}$$

Higher levels of income loss are expected to increase the likelihood of strongly agreeing to experiencing emotional stress while income recovery is expected counteract to stress. We suspect that a higher income bracket will reduce the likelihood of strongly agreeing to experiencing emotional stress since a higher income may provide greater resources to cope with the impacts of income losses. We expect that individuals who strongly agreed that their cultural traditions had been impacted by the HAB event will have a greater likelihood of strongly agreeing to experiencing emotional stress than individuals who did not strongly agree that their cultural traditions had been impacted. In addition to the expectation that cultural impacts would trigger emotional stress, this may reflect the propensity of an individual to answer these survey questions similarly. We suspect that the emotional stress associated with the alternate adaptive actions will depend on the degree to which an individual is accustomed to the activity. Finally, we expect that coping actions (borrowing, obtaining assistance, and defaulting on payments) will increase the likelihood of strongly agreeing to experiencing emotional stress.

FINDINGS

Income Loss

Greater exposure to the 2015 HAB event, as measured by the proportion of commercial Dungeness crab fishing season lost, increased the probability of experiencing high absolute income losses (>\$10,000). On average, an increase of one standard deviation in the HAB index (equivalent to approximately a quarter of a fishing season) was associated with an 8–11% increase in the probability of experiencing high income losses ($p < 0.01$) (**Supplementary Tables A2, A3**). Income losses were also controlled by the level of income dependence on shellfish and typical income level. Increases in income dependence and a higher income bracket were associated with an increased probability of greater income losses (**Supplementary Table A2**).

Fishers were more likely to experience high income losses than hospitality providers given the same level of HAB exposure. Over the range of HAB exposures experienced during the 2015 event (a loss of between 10 and 70% of the commercial Dungeness crab fishing season), a fisher's predicted probability of high income losses increased from 0.40 to 0.65. In comparison, this probability ranged from 0.19 to 0.30 for a hospitability provider (**Figure 1**). On average, the predicted probability of high income losses was increased by 0.26 for fishers relative to hospitality providers ($p < 0.01$) (**Supplementary Table A2**).

Business ownership also influenced the outcome of income losses. All else the same, business ownership was associated with a 0.20 increase in the probability of experiencing high income losses ($p < 0.01$) (**Supplementary Table A2**). Among fishers, the probability of high income losses for fishing license owners/operators was increased 0.39 relative to deckhands ($p < 0.01$), 0.25 relative to fish processors ($p < 0.05$), and 0.33 relative to fish retailers ($p < 0.01$) (**Supplementary Table A2**).

A typical fishing license owner (with a medium income level and a shellfish dependence of 50–74% of their annual income) operating in California, where the median fisheries closures lasted 72% of the season, had a predicted probability of high income losses of 0.85 (**Figure 2A**). In comparison, for fish retailers, processors and deckhands in California this probability ranged between 0.40 and 0.59. In Oregon and Washington where the fishery closures lasted only 12 and 13% of the season, respectively, the predicted probability of high income losses were lower (**Figure 2B**) with fishing owner/operators facing probabilities of approximately 0.50.

Income Recovery

The level of income loss and engagement in adaptive actions influenced the likelihood of income recovery

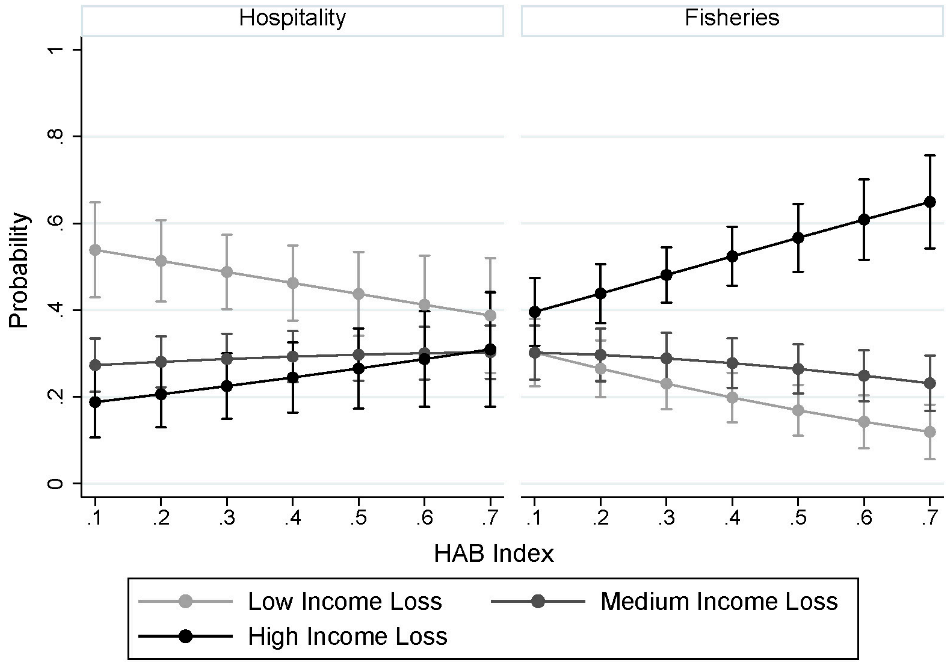

FIGURE 1 | The effect of HAB fisheries closure extent on the probability of income loss level by employment industry.

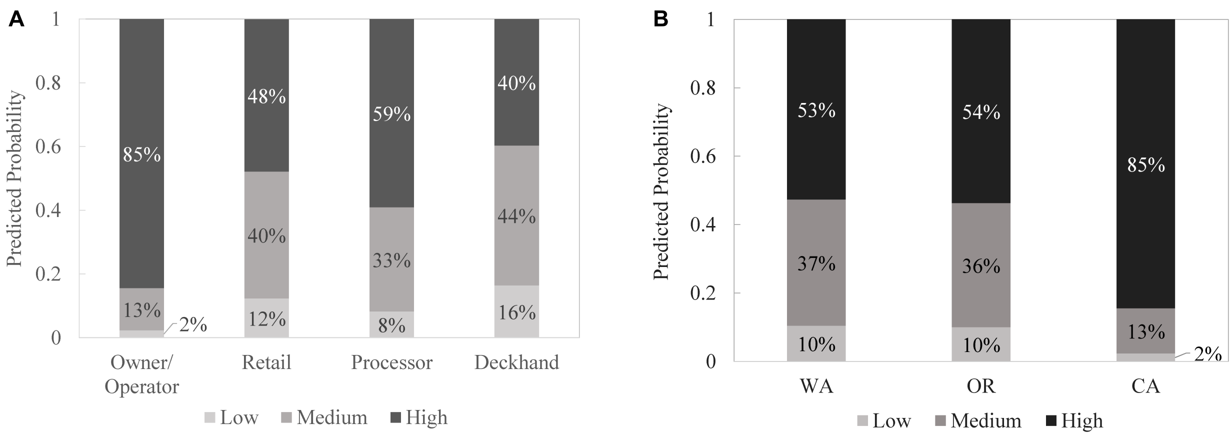

FIGURE 2 | The predicted probability of income loss level for typical fishers in California by fishing job type **(A)** and a typical fishing license owner/operator by State **(B)**.

(**Supplementary Tables A4, A5** and **Figure 3**). As expected, higher absolute levels of income loss were associated with a lower probability of loss recovery. Compared to low income losses, the probability of recovery was decreased by 0.38 ($p < 0.01$) for high income losses and by 0.20 ($p < 0.05$) for medium income losses. Across fishers only, high income losses were associated with a decrease in the probability of loss recovery of 0.44 relative to low losses and 0.25 relative to medium losses ($p < 0.01$ for both effects). However, having accounted for other factors, the model found no evidence that fishers were more or less likely to recover income losses than hospitality providers.

Adaptive actions such as taking a side job, fishing for alternate species or in alternate locations, and advertising business more widely were associated with an increased probability of income recovery (**Supplementary Table A4** and **Figure 3**). Advertising was found to be a particularly effective adaptive strategy. The associated increase in the probability of income recovery was 0.44 across all survey respondents and 0.40 across fishers only ($p < 0.01$ for both effects). In comparison, engaging in modified fishing activities increased the probability of income recovery by 0.25 across all survey respondents and 0.28 across fishers only ($p < 0.01$ for both effects). Obtaining a side job was found to increase the probability of income recovery by 0.17 across all

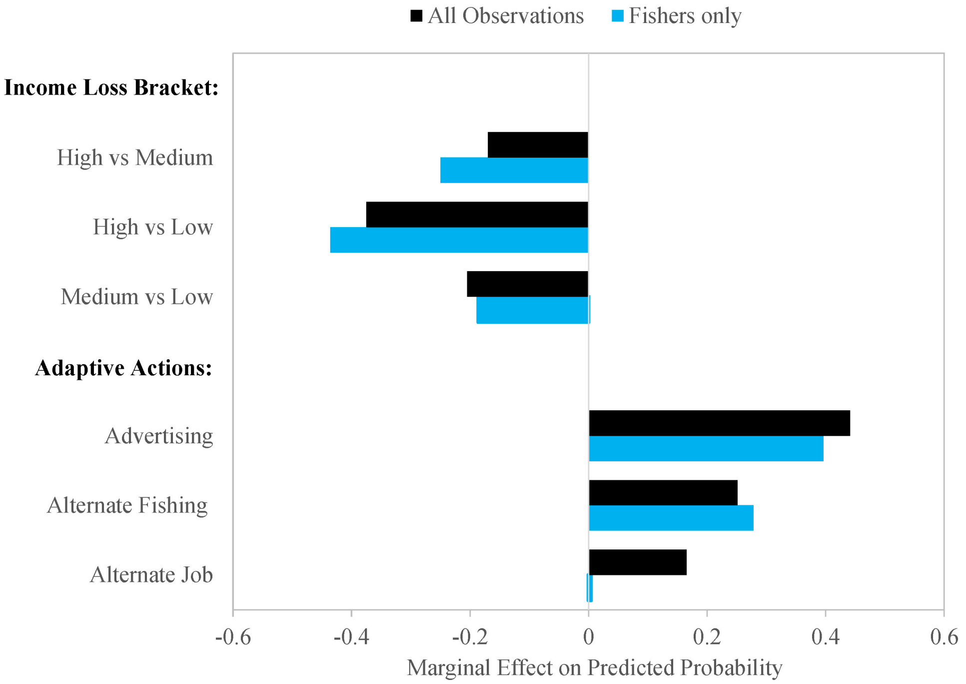

FIGURE 3 | The effect of income loss level and adaptive actions on the probability of income loss recovery. All effects are statistically significant ($p < 0.1$) apart from alternate job for fishers.

survey respondents, but there was no evidence this strategy was effective across fishers only.

Emotional Stress

Strongly agreeing to experiencing stress was associated with both the level of income loss as well as the ability to recover those losses (**Supplementary Tables A6, A7** and **Figure 4**). All else the same, high income loss increased the predicted probability of strongly agreeing to experiencing stress by 0.20 ($p < 0.05$) compared to low income loss in the model across all observations. This marginal effect increased to 0.31 ($p < 0.01$) across fishers only. Conversely, the ability to recover income losses was associated with a decrease in the predicted probability of strongly agreeing to experiencing stress. This decrease was estimated as 0.17 ($p < 0.05$) across all observations and 0.29 for fishers only ($p < 0.01$).

Engaging in some adaptive or coping actions were associated with an increase in the probability of strongly agreeing to experiencing stress (**Supplementary Table A6** and **Figure 4**). Defaulting on existing loans or payments was associated with an increase of 0.30 ($p < 0.01$) in the predicted probability of strongly agreeing to experiencing stress in the model across all survey respondents. This marginal effect decreased to 0.24 ($p < 0.05$) for fishers only. The model for fishers only also found that advertising and obtaining a side job were associated with strongly agreeing to experiencing stress. On average, a fisher's probability of strongly agreeing to experiencing stress was increased by 0.40 ($p < 0.01$) with obtaining a side job and by 0.28 ($p < 0.05$) with advertising.

Cultural impacts were also associated with an increased probability of strongly agreeing to experiencing stress (**Supplementary Table A6** and **Figure 4**). Survey participants who strongly agreed that their family gatherings, holidays or traditions had been negatively impacted due to a lack of shellfish to eat had a 0.13–0.17 (depending on model specification) higher predicted probability of strongly agreeing to experiencing stress relative to survey participants who did not strongly agree that their cultural traditions had been impacted by the HAB event ($p < 0.05$ for both estimates).

DISCUSSION

Our findings fill a critical knowledge gap by empirically identifying factors that contribute to an individual's vulnerability to HAB events. Individuals who suffered greater absolute income losses were exposed to longer fisheries closures, more dependent on shellfish as a source of income, employed in the fishing industry, and owned their business. Our results also hint at the importance of the timing of the fishery closures. The 2015 HAB event closures occurred during peak season, which likely exacerbated income losses (Ritzman et al., 2018). While the fishery closures lasted only 12 and 13% of the season in Oregon and Washington, respectively, the probability of income losses greater than $10,000 was still over 0.50 for a typical fishing license owner in both States.

The finding that greater income dependence on shellfish was associated with higher absolute income losses supports the

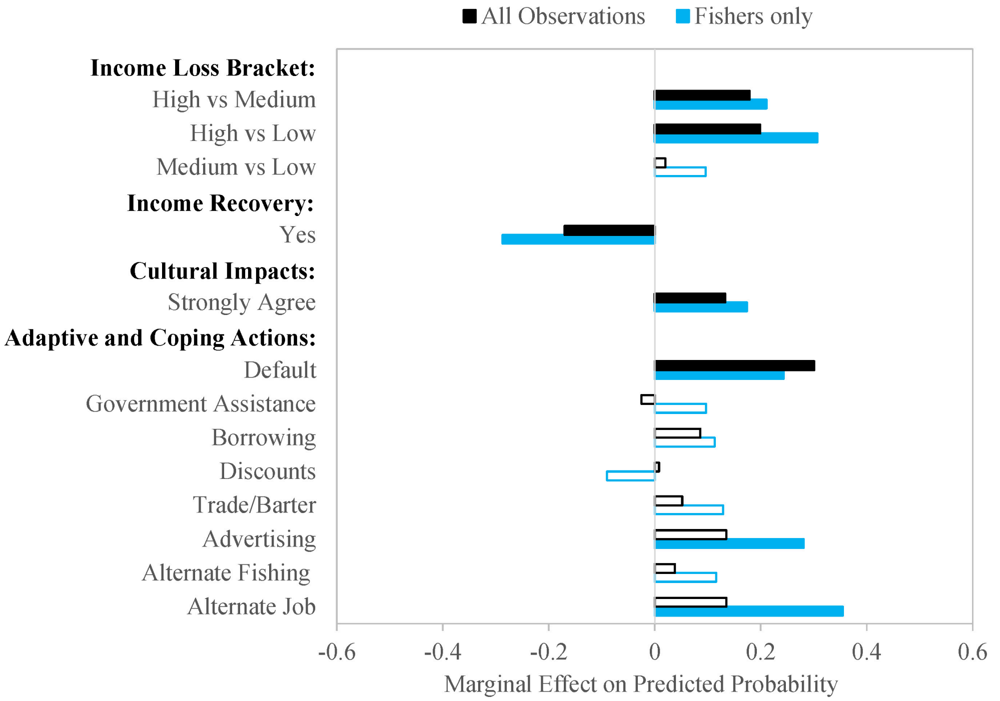

FIGURE 4 | The effect of income loss level, income loss recovery, cultural impacts, and adaptive and coping actions on the probability of strongly agreeing to experiencing stress. Statistically significant ($p < 0.1$) effects are illustrated with solid bars while hollow bars represent statistically insignificant effects.

argument that income diversification can increase resilience to resource disruptions such as HAB events (Kasperski and Holland, 2013; Sethi et al., 2014; Aguilera et al., 2015; Cline et al., 2017). Diversification of the fishing fleet may entail costs and regulatory restrictions – imposed on both an individual and society – that need accounting for. Costs to fishers include the purchase of permits and new gear for different fisheries as well as additional travel and time costs if the new fisheries are further afield (Kasperski and Holland, 2013; Sethi et al., 2014; Cline et al., 2017). Fishers participating in diverse fisheries may also suffer a loss of efficiency if they lack either fishery-specific knowledge or an optimized vessel (Kasperski and Holland, 2013; Cline et al., 2017). In addition to costs, regulatory restrictions such as limited access programs may prevent individuals from entering new fisheries (Kasperski and Holland, 2013; Holland and Kasperski, 2016; Cline et al., 2017). However, in the absence of these programs, diversification of the fishing fleet could have ecological consequences if new fisheries faced increased fishing pressure. The Magnuson-Stevens Fishery Conservation and Management Act requires that "conservation and management measures shall…take into account the importance of fishery resources to fishing communities…in order to (a) provide for the sustained participation of such communities, and (b) to the extent practicable, minimize adverse economic impacts on such communities" (National Marine Fisheries Service, 1996). If increasing the adaptive capacity of fishing communities to HAB events is a policy goal, then management for fisheries conservation will need to be carefully balanced with fishing diversification (Kasperski and Holland, 2013; Aguilera et al., 2015).

Income diversification can also include non-fishing sources (Kasperski and Holland, 2013; Sethi et al., 2014) and may occur at either the individual or household level (Allison and Ellis, 2001). For households, the burden of providing a reliable income to counter the variability of fishing revenue often falls disproportionately on women (Frangoudes and Gerrard, 2018). We see some indication of this in the full survey dataset with respondents noting that their household was able to cope with HAB-related income losses because a female member of the household earned a non-fishing income. The extent to which non-fishing income sources can buffer household losses will depend on the degree to which the income source is associated with the fishing industry and the pervasiveness of economic effects within a community (Ritzman et al., 2018).

The effectiveness of alternate actions to recover income losses differed depending on employment sector. While advertising and alternate fishing activities were useful strategies for both fishers and hospitality providers, obtaining a side job was associated with an increased probability of income recovery for hospitality providers only. Alternate fisheries targeted by survey respondents included sablefish, salmon, sardines, and tuna. The survey did not provide information on the kinds of advertising pursued. Given the effectiveness of this adaptive action for both fishers and hospitality providers, future work could usefully investigate this. Side jobs pursued by survey respondents varied widely and included cutting firewood, door to door yard work, construction, carpentry, and auto repair (only 35% of survey respondents who took a side job indicated what kind). The emotional stress associated with alternate adaptive actions also differed by employment sector. While advertising was associated with stress for fishers, engaging in alternate fishing activities was not. This may reflect the fact that the individuals who engaged in alternate fishing activities were already prepared for (i.e., had access to gear and the appropriate permit) and accustomed to this activity; most inshore fishermen around the world have diversified fishing strategies (Allison and Ellis, 2001) including those in the contemporary Pacific Northwest (Cline et al., 2017). It may also indicate that being able to engage in other fishing activities does not trigger stress because occupational identity and cultural norms are sufficiently maintained. It is notable that while finding alternate employment was associated with stress for fishers, there was no evidence of increased stress from this action across all survey participants. This may suggest that occupational identity is less important for hospitality providers than for fishers (Pollnac and Poggie, 2008). Since an individual's propensity to engage in adaptive action is likely influenced by associated stress, these findings highlight the importance of documenting emotional stress and cultural impacts in additional to economic outcomes.

Our findings regarding emotional stress are consistent with reported responses to other sorts of major disruptions to coastal communities, for example, oil spills. Oil spills share some similarities with HABs in that they are unexpected events, can cover large areas, are of uncertain duration, and can trigger management actions that are independent of metrics such as stock size or total allowable catch. Evidence from response to major oil spills in Alaska and in the Gulf of Mexico indicates that the negative effects on well-being were profound, despite large differences in the ecological, oceanographic, and sociological contexts of the two spills. For example, the Exxon Valdez Oil Spill, which affected communities along more than 800 miles of coastline in the Gulf of Alaska, eroded both the emotional and physical health of those in coastal communities, whether or not they were directly engaged in fishing. These effects appeared to follow a dose-response curve, with those more exposed to spill effects suffering the greatest impact (Palinkas et al., 1993). Evidence from the Deepwater Horizon Oil Spill revealed that emotional stress was associated with the extent to which lives, livelihoods, and social engagement were disrupted, and that those who suffered economic losses were at higher risk of emotional distress than those who did not (Osofsky et al., 2011). Indeed, loss of income appeared to be the primary driver of anxiety and depression among those affected by the spill (Morris et al., 2013).

The finding that business owners fared worse than employees was contrary to that suggested in interviews conducted prior to the survey (Ritzman et al., 2018). This may point to the possibility that employees, typically hospitality employees and deckhands, who fared poorly had already relocated by the time the survey was deployed and/or were not successfully recruited with the online survey methodology. We suspect that deckhands and hospitality employees may have been particularly vulnerable because they are typically the first to lose their jobs if employers suffer ongoing losses and they are less likely to have the means to cope with extended disruptions to their livelihood (Ritzman et al., 2018), and if so, our survey failed to capture this. At the same time, it is possible that business owners may be less flexible in engaging in adaptive actions, which were not included in the model of income loss due to endogeneity concerns. As noted above, the same could be true for fishers compared to hospitality providers.

The results from the models developed in this study should be interpreted with caution due to the sample size and a potential lack in the representativeness of the survey participants. While the sample size is large compared to previous research into the societal impacts of HABs, the number of observations is still relatively low for statistical analysis (Long and Freese, 2014). Moreover, the survey data should not be generalized outside of our specific sample given that our sampling technique was not based on random sampling and may be affected by voluntary and non-response bias. The survey captured fewer hospitality providers than fishers and a relatively small number of deckhands and hospitality employees. Our analysis was also limited by an inability to estimate the proportion of income an individual lost due to the HAB event. This limits our understanding of the financial impact experienced by an individual, particularly those at lower income levels who might have lost all or most of their income due to the HAB event. Finally, the survey only provided binary data on whether losses were fully recovered or not. This could have caused downward-bias on our assessment of the effectiveness of adaptive efforts. Despite these limitations, this study is an important step forward in identifying effective solutions to increase the resilience of individuals and communities to HAB events.

CONCLUSION

Harmful algal bloom events are expected to increase in intensity and occur more frequently with current trends in global ocean conditions. These trends threaten the livelihood of fishery-dependent coastal communities. We aimed to develop a mechanistic understanding of an individual's vulnerability to HAB events and to identify effective solutions. Our findings suggest that income diversification and adaptive actions such as increased advertising, alternate fishing, and obtaining a side job could improve resilience to HAB events. The effectiveness of alternate adaptive actions to recover income losses differed by employment industry. Advertising and alternate fishing activities were found to be effective strategies for both fishers and hospitality providers, while obtaining a side job benefited only hospitality providers. These actions also differed in emotional cost. While there was no evidence of increased stress associated with alternate fishing activities, advertising and finding alternate employment were associated with stress for fishers. If increasing the adaptive capacity of fishery-dependent coastal communities to HAB events is a policy goal, then costs to adaptive action such as emotional stress, limited access to alternate fisheries, new fishing gear, a lack of alternate job skills or access to job networks, and a lack of advertising know-how will need to be addressed.

More work is needed to assess these potential barriers and to determine the applicability of the findings drawn here to future HAB events both on the United States West Coast and elsewhere.

DATA AVAILABILITY STATEMENT

The raw datasets for this manuscript are not publicly available because they could violate human privacy. Requests to access de-identified data should be directed to TK, tklinger@uw.edu.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Washington, Human Subjects Division. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and design of the study and manuscript revision, and read and approved the submitted version. KM performed the statistical analysis and wrote the first draft of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00803/full#supplementary-material

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