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Inequality in the economic impacts from climate shocks in fisheries: the case of harmful algal blooms

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Abstract

Climate impacts disproportionately affect people that are most vulnerable and least able to adapt. The extent to which these equity impacts extend to fishing communities in the developed world is a question that has received surprisingly little attention. Here we explore the distributional impacts of a climate shock in one of the largest and most valuable fisheries on the West Coast of the United States. Specifically, we examine whether a series of two harmful algal blooms (HABs), occurring during the 2014-2016 Northeast Pacific Marine Heatwave, differentially affected small and large vessels in the commercial California Dungeness crab fishery. The HAB events were managed with localized fishery closures in response to elevated levels of the HAB toxin, domoic acid, in crab tissue. We find evidence that large vessels had a greater ability to mitigate losses from the HAB events. Thus, the proportion of total revenue going to small-vessel operators and the proportion of small-vessel participation in the fishery fell in response to the HAB events in several California fishing ports. Our results, therefore, offer empirical evidence that climate impacts on fishing communities are not uniform and offer insights into potential alternative adaptation strategies for different ocean user groups.

Keywords: Climate change, Dungeness crab, fisheries, harmful algae, harmful algal blooms, fishery management, economic impacts, equity.

1. Introduction

The societal impacts of climate change are likely to be disproportionately borne by populations that are most vulnerable and least able to adapt (Mendelsohn, Dinar, & Williams, 2006; Mendelsohn, Emanuel, Chonabayashi, & Bakkensen, 2012; Park, Hallegatte, Bangalore, & Sandhoefner, 2015; Winsemius et al., 2015; Hallegatte & Rozenberg, 2017). Inequities in the distribution of climate impacts across a population, hereafter referred to as the "distributional impacts" of climate variability and change, are potentially compounded for vulnerable populations due to a greater dependence on natural resources (Paavola & Adger, 2002; Adger, Huq, Brown, Conway, & Hulme, 2003) and a lack of social, financial, and other resources to cope with and adapt to environmental change (Kates, 2000; Cutter, Boruff, & Shirley, 2003; Hallegatte & Rozenberg, 2017).

Fishers and fishing communities are closely connected to the environment and are expected to be impacted by climate change in numerous ways (see Hollowed et al. (2013) for a review). Key impacts of climate change on fisheries include shifts in the geographic distribution of fish species that will disrupt fisheries in regions that become uninhabitable for certain fish species (A. L. Perry, Low, Ellis, & Reynolds, 2005; Pinsky, Worm, Fogarty, Sarmiento, & Levin, 2013; Morley et al., 2018) and changes in fisheries productivity (e.g. Britten, Dowd, & Worm, 2016) which will alter biological reference points used in management, e.g. maximum sustainable yield (Cheung et al., 2010). Climate change is also expected to directly affect fisheries via its impacts on seafood safety through, for example, climate-driven changes in the frequency, magnitude, and geographic scope of harmful algal blooms (HABs) (Hallegraeff, 1993, 2010; Moore et al., 2008; Backer & Moore, 2010; Marques, Nunes, Moore, & Strom, 2010; Berdalet et al., 2016).

HABs occur when colonies of algae proliferate and cause damage to the environment and/or produce toxic effects on people and other marine and aquatic life

(Erdner et al., 2008). Many HABs produce toxins that accumulate in shellfish, and while they may not jeopardize shellfish survival, predators such as marine mammals and humans may suffer illness or death if contaminated shellfish are consumed. These HAB events are managed with fishery closures that are effective at preventing human exposure to HAB toxins and protecting human health, but can cause severe economic and sociocultural disruption to fishery-dependent communities (Bauer, 2006; Ritzman et al., 2018).

Understanding the economic and distributional implications of climate change in fisheries and fishing communities is critical as fisheries managers balance multiple, and often competing, goals including achieving biological sustainability and promoting economic efficiency and equity (Charles, 1992; Rosenberg, Fogarty, Sissenwine, Beddington, & Shepherd, 1993; Kailin Kroetz, Sanchirico, & Lew, 2015). Equity impacts depend on both climate-driven changes to fisheries and individual-, fleet-, and community-level adaptive responses to these changes. For example, the economic impacts of species range shifts and productivity changes depend on the ability of individual fishers to adjust spatial harvest patterns, change gear types, and/or target new species (Sumaila, Cheung, Lam, Pauly, & Herrick, 2011; Pinsky & Fogarty, 2012). Most of our knowledge of the distributional impacts of climate change on fisheries comes from examples in the developing world, with surprisingly little attention given to developed-world fisheries.

Here we explore a case study of the distributional impacts of the 2014-2016 Northeast Pacific Marine Heatwave that resulted in a series of two toxic HABs (caused by species in the marine diatom genus *Pseudo-nitzschia*) that severely impacted the commercial Dungeness crab fishery. The Dungeness crab fishery is among the most valuable on the U.S. West Coast, with annual ex-vessel revenues in the hundreds of millions of dollars. Prior to the two HAB events examined here, all of the previous major *Pseudo-nitzschia* HAB events on the West Coast have occurred after periods of warming associated with El Nino and the Pacific Decadal Oscillation (McCabe et al., 2016; McKibben et al., 2017), providing evidence for a relationship between warming and extreme HABs. Therefore, continued warming due to climate change may worsen HABs of *Pseudo-nitzschia* on the West Coast, potentially leading to longer, more frequent, and more widespread fishery closures.

The two HAB events explored here occurred in 2015 and 2016, impacting the 2015/2016 and 2016/2017 Dungeness crab fishing seasons, respectively. The HAB events were managed with localized fishery closures, that were sequentially opened once the crab in their boundaries were deemed safe for human consumption. Opening individual areas while others remain closed introduces heterogeneity in fishing opportunities based on geography as well as characteristics of individual vessels and fishing businesses. Additionally, extended closures can compress the fishing season to the advantage of vessels with a greater capacity for speed in harvest.

We ask the question: were economic impacts of the 2015 and 2016 HAB events, and the corresponding management response, equally shared across the commercial Dungeness crab fishing fleet in California? We focus on the differences between impacts to small and large vessels, with small vessels defined as less than 40 feet in length, or less than roughly 12.2 meters. Small vessels have been shown to be less profitable (McCay, 2004), receive lower returns to their labor inputs (Boncoeur, Coglan, Le Gallic, &

Pascoe, 2000), and can be restricted in their ability to respond to geographic shifts in fishing opportunities due to reduced mobility (Young et al., 2019), suggesting that small-vessel operators and communities dominated by small fishing vessels may also be less resilient to climate shocks.

Our analysis draws on data collected for every Dungeness crab delivery, by both small and large vessels, in California from the 2010/2011 through the 2016/2017 fishing seasons. First, we explore evidence of spatial shifts in vessel deliveries patterns and, if shifts are detected, whether those shifts are consistent with the idea that large vessels had an increased ability to respond to localized fisheries closures during the two HAB events. Second, we estimate the changes in distributional outcomes, measured in terms of revenue and participation, associated with the two HAB events.

Our results can inform the design of future fisheries policies that aim to promote equity in a world of environmental change. Our findings also highlight the importance of both communities-of-place, such as individual ports, and communities-of-practice, such as groups of vessels with similar characteristics and constraints, in developing management strategies that meet equity objectives in the face of climate shocks (Martin & Hall-Arber, 2008).

2. Background and Data

Dungeness crab is the most valuable fishery on the U.S. West Coast. In California specifically, the fishery generated average ex-vessel revenues of roughly $60 million USD over the last decade. California Dungeness crab are harvested in a limited-entry derby fishery characterized by overcapitalization (Hackett, Krachey, Dewees, Hankin, & Sortais, 2003) and a compressed season length where the majority of crab is landed during the first 6 weeks of a 7-month season (Dewees et al., 2004). Despite the current race to fish and the implied opportunity to improve profitability in this fishery, the Dungeness crab fishery is an important source of income for participants. In a survey of California Dungeness crab permit holders, over 80% of respondents stated that over 60% of their gross income came from fishing Dungeness crab (Dewees et al., 2004).

The Dungeness crab fishery is managed at the state level with a ban on female harvest, size restrictions on the harvest of male crabs, and seasonal closures to protect molting crab (Porzio, 2015). The California Dungeness crab fishery is divided into northern and central management districts at the Mendocino-Sonoma County border. The central management district coincides with fishing district 10 and the northern district is further subdivided into fishing districts 6 (Crescent City and Eureka), and 7 (Fort Bragg). The central California season runs from November 15th through June 30th and the northern California season runs from December 1st through July 15th. The season opening dates are subject to delay if meat content is below established threshold values (i.e. < 25%) or if levels of the HAB toxin, domoic acid, are higher than established regulatory thresholds (> 30 ppm in crab viscera).

Due to concern that season delays would allow some vessels to target multiple openings and disadvantage vessels in delayed areas, Fair Start Provisions were established in 1997 (Cal. Fish and Game Code FGC § 8279.1). The law maintains that, with season delays of a California fishing district, persons landing Dungeness crab outside of that district must wait 30 days after the delayed district opens before landing crab in the delayed district. For example, if a district was delayed, individuals that had previously fished outside of that district, either in another California fishing district or in

Oregon or Washington, would have to wait 30 days after the delayed district was opened before participating in the delayed district, thereby affording the delayed district 30 days of protections. Importantly, the regulations, as applied to the 2015/2016 and 2016/2017 seasons, stipulated that the open date for a delayed district is the date on which any part of the delayed district is open to fishing.[1] In 2018, the law was amended to apply to any delayed area regardless of whether the area is in a district that had previously opened.

The 2014-2016 Northeast Pacific Marine Heatwave, otherwise known as the "Blob", extended from Alaska to Mexico and produced peak near-surface (upper ~ 100 m) seawater temperature anomalies of 2.5°C, exceeding 3 standard deviations from normal (Bond et al. 2015). The anomalously warm water caused a number of unusual biological events, including a massive HAB of *Pseudo-nitzschia* that began in the spring of 2015 and resulted in multiple fishery closures along the entire West Coast for many species of fish and shellfish, including Dungeness crab, due to unsafe levels of domoic acid (McCabe et al., 2016). Closures in the California Dungeness crab fishery were more severe than in Oregon and Washington, lasting nearly 4.5 months in the 2015/2016 season. The 2016/2017 season was also delayed due to elevated levels of domoic acid in California Dungeness crab, but the incidences were relatively localized, and closures were shorter in duration and only implemented in a subset of California ports.

Figure 1 shows the rollout of the commercial Dungeness crab season openings for the 2015/2016 and 2016/2017 fishing seasons. In the 2015/2016 season, the central district opened on March 26th, roughly 4.5 months late. It was not until 36 days later (May 12th) that the northern district, with the exception of Eureka, was open to fishing.

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[1] On January 1st, 2017 FGC § 8279.1 was amended so that the law applied to vessels rather than persons.

Eureka was finally open on May 26th, or 50 days after the central district opened. The extended delays in the 2015/2016 season shortened the season length relative to previous seasons by pushing the season into the period when crabs begin to molt and the season is officially closed.

The timing of HAB closures and protections under the Fair Start Provisions in the 2015/2016 and 2016/2017 seasons varied over space. Specifically, in the 2015/2016 fishing season all fishing districts were considered delayed and protected under the Fair Start Provisions. However, a section of district 6, containing Crescent City, opened on May 12th while the remainder of district 6, containing Eureka, opened on May 26th. Thus, according to the Fair Start Provisions, individuals who had landed Dungeness crab in other California districts, or in Oregon or Washington, were eligible to fish in any part of district 6 on June 11th, providing the Crescent City area with 4 weeks of protection and the Eureka area with roughly 2 weeks of protection. In summary, extended delays in the 2015/2016 season led to greater compression of season length and, while all 3 fishing districts were delayed in the 2015/2016 season, the Eureka area experienced the longest delays and least protections under the Fair Start Provisions.

In the 2016/2017 season, the central district, with the exception of Bodega Bay, opened on time (November 15th). In the northern district, Crescent City and Eureka opened on time (December 1st), Bodega Bay area was delayed until December 3rd, and the Fort Bragg area was opened in sections with the first opening on December 26th and the final opening on January 16th. In this fishing season, only fishing district 7 (Fort Bragg) was protected under the Fair Start Provisions, because even though Bodega Bay was delayed, Bodega Bay is within the central district (fishing district 10) some of which opened on time. Additionally, the 30-day fair start waiting period for Fort Bragg ended on January 25th, offering only 9 days of protection to the last section of the Fort Bragg area to open.

There were several mechanisms by which the two HAB events potentially affected outcomes for small vessels. First, the compressed length of the 2015/2016 season may have affected small vessels if the ability to compete in a compressed season is driven by vessel size. Second, in the 2015/2016 season, spatial spillover of vessels from Eureka (the area with the longest delays) to other ports may have may have disproportionately increased competition for small vessels in other ports. Third, in the 2015/2016 season, small vessels based out of Eureka may have faced increased competition from large vessels fishing in multiple areas if large vessels took advantage of the relatively short period of protections under the Fair Start Provisions. Fourth, in the 2016/2017 season, the delayed opening of Bodega Bay may have been interpreted as a signal that northern California districts would again face extended delays, for a second consecutive season. Larger, mobile vessels responding to this signal could have left northern port areas and increased competition for small vessels in other areas. Fifth, when Bodega Bay finally opened in the 2016/2017 season, it was not protected under the Fair Start Provisions, therefore larger, more mobile vessels participating in multiple openings could participate in the Bodega Bay opening without restrictions, enhancing competition for small vessels. Sixth, the gradual opening of the Fort Bragg area may have created opportunities for larger, more mobile vessels to make their way up north and participate in multiple openings, enhancing competition for small vessels as they went.

Indeed, fishers reported that the larger and most mobile vessels were able to participate in multiple openings, providing anecdotal evidence of distributional impacts from the climate shock (Callahan, 2017a, 2017b). Our analysis seeks to explore the empirical support behind these anecdotal reports. Specifically, we quantify the impact of the HAB closures in the 2015/2016 and 2016/2017 seasons on three response variables: 1) spatial landings patterns for small and large vessels; 2) the proportion of total revenue going to small vessels; and 3) the proportion of small vessels participating in the fishery relative to total participation. Vessel landings and revenue data come from confidential fish tickets, collected by state managers, and archived in the PacFIN database housed at the Pacific States Marine Fisheries Commission (PSMFC). The fish ticket data are essentially sales receipts generated upon the delivery of a harvester's landings to a processor. We match the fish ticket data with state data on vessel registration, which includes vessel length. Large vessels are defined as vessels ≥ 40 feet in length following Kasperski and Holland (2013). We first filter the data to remove any observations outside of the legal fishing season. We then aggregate landings data, for small and large vessels, to the week and port-group level, where port groups are defined by the PSMFC (see Figure 1).[2] Our dataset covers all landings in the 2010/2011 through 2016/2017 fishing seasons, allowing us to observe outcomes before and after the HAB closures, utilizing the before-period observations in a counterfactual analysis.

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[2] Port group definitions can be found at https://pacfin.psmfc.org/pacfin_pub/data_rpts_pub/code_lists/pc_tree.txt.

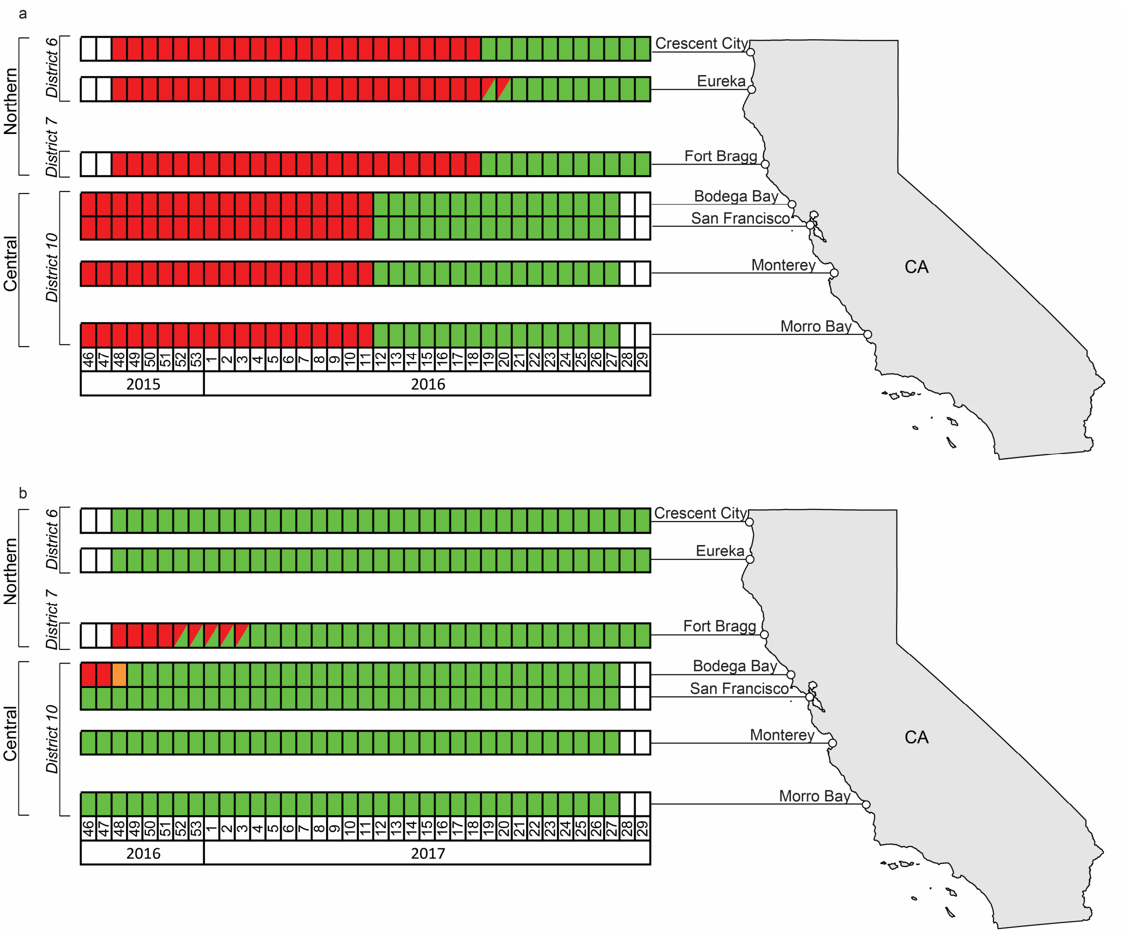

Figure 1: Map of California Dungeness crab port group closures in the 2015/2016 season (top panel) and 2016/2017 season (bottom panel). Grid cells represent weeks that the port area is opened to fishing in absence of any delays. Red represents the entire week in the port area is closed due to HABs, yellow represents a fraction of the week was delayed due to HABs, and green represents an open fishery. Cells that are half red and half green mean that a fraction of the port group was open for the entire week and a fraction of the port group was closed for the entire week.

3. Methods

3.1 Examining Distributional Shifts in Landings

As a first step, we examine spatial shifts in Dungeness crab pounds landed during the 2015/2016 and 2016/2017 seasons. We create a "baseline" profile for each vessel, measuring the proportion of Dungeness crab pounds (based on fish tickets) landed at each port group. This baseline represents vessel behavior over a 3-season period (fishing seasons 2011/2012, 2012/2013, and 2013/2014).[3]

We use the baseline landings profiles to separately group large and small vessels with similar delivery patterns, applying a k-means clustering analysis to the 3-season baseline period. We perform two cluster analyses in total using baseline landings for all vessels falling into each of the following groups: (1) small vessels active in 2015/2016 and/or 2016/2017; and (2) large vessels active in 2015/2016 and/or 2016/2017. Thus, in order to be included in the analysis, a vessel must have been active in at least one HAB season and at least one baseline season. The criteria exclude 9% and 11% of vessels active in the 2015/2016 and 2016/2017 seasons respectively.

Clusters identified in the analysis represent groups of vessels with similar spatial landings patterns, which are then used to assign a “homeport” to each vessel. In this context, homeport is defined as the port group at which a vessel landed a majority of its catch, of Dungeness crab, during the baseline period. The dissimilarity matrix for the clustering analysis was calculated using a Bray-Curtis distance (Bray & Curtis, 1957), which is well suited for data where multiple abundance or coverage measures characterize a single unit. We use the Ward method (Ward Jr & Hook, 1963) for clustering and determine the optimal number of clusters using a combination of screeplots, the Tibshirani et al. (2001) gap statistic, and visual assessments of heatmaps showing delivery frequencies per port group during the baseline period.

The cluster analysis allows us to examine evidence for a spatial shift in Dungeness crab pounds landed the two HAB seasons, relative to the “before” period (or

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[3] We exclude the 2014/2015 season from our baseline period, used to define a vessel’s home port, because shifts in the spatial distribution of Dungeness crab (from north to south) led to changing deliveries patterns and vessels fishing outside of their homeports (Spencer, 2014).

the 2010/2011-2014/2015 seasons), for groups of vessels assigned to the same homeport.[4] The spatial shift in pounds delivered for each cluster is calculated as the difference in the proportion of pounds delivered to each port group during the 2015/2016 and 2016/2017 seasons and the proportion of pounds delivered to each port group in the before period. We descriptively analyze the sign and magnitude of these spatial shifts in pounds delivered for small and large vessels using heatmaps. Note that for confidentiality reasons, results with fewer than three vessels in a homeport/landing port combination are not shown. Therefore, for example, if two vessels from a given homeport shifted all of their landed pounds into another port, these shifts would not be recorded in the heatmap. Note also that the heatmaps will show the changes in total proportions over a season. It does not show intra-seasonal dynamics, which may be important in this context, but are beyond the scope of our analysis.

3.2 Estimating Impacts with Robustness Checks

To estimate the impacts of the two HAB events on the small-vessel proportions of revenue and participation, we use a "before/after" analysis, an approach which has been implemented in numerous program evaluations of fisheries including the impact of catch shares on trip costs and revenues (Kroetz and Sanchirico 2010) and diversification (Holland et al., 2017), and the impact of HABs on seafood prices (Jin, Thunberg, & Hoagland, 2008).[5] Our two outcome variables of interest, the small-vessel proportions of revenue and participation, are naturally bounded between zero and one. Thus, to account

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[4] Note that the "before" period (2010/2011-2014/2015) is different than the baseline period (2011/2012, 2012/2013, and 2013/2014).

[5] There are similarities in our methods and data to those in Perry (2018) except for that our before-after analysis is done in a regression framework, our data set was based on the confidential fish ticket data with fewer missing observations, and our dataset covers the entire 2016/2017 season.

for the bounded nature of the data, following Papke and Wooldridge (1996) and Hausman and Leonard (1997), we use fractional response models to estimate the impact of the HAB events on small vessel revenue and participation in California. We estimate both average effects, averaging across all port groups, and heterogeneous port-specific effects with the following models:

Average effects:

$$E(y_{it} \mid A_t, \mathbf{X}_{it}, \tau_t, \lambda_i) = F(A_t\delta, \mathbf{X}_{it}^{'}\beta, \tau_t, \lambda_i), \qquad (1)$$

Heterogeneous effects:

$$E(y_{it} \mid A_{it}, \mathbf{X}_{it}, \tau_t, \lambda_i) = F(A_{it}\delta_i, \mathbf{X}_{it}^{'}\beta, \tau_t, \lambda_i), \qquad (2)$$

where y_{it} is the outcome variable for the port-group of landings i in season t, which is either the fraction of total revenue generated by small vessels or the fraction of the total unique vessels participating in the fishery that are classified as small vessels; A_t is a dummy variable set equal to one for all observations in the “after” or “treatment” period, i.e. during a HAB event; A_{it} are dummy variables set equal to one for observations in port groups i in the treatment period (i.e. it is the interaction between being in the treatment period A_t and a port-group fixed effect); $\mathbf{X}_{it}$ are controls for port-specific season trends that can account for trends in outcomes over time at a specific port (e.g. trends in the relative revenues of small vessels delivering to the San Francisco port);[6] τ_t are controls for fishing week fixed effects that can account for temporal drivers of outcomes within a

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[6] Port-specific time trends are calculated by interacting the season number (season numbers for seasons 2010/2011 – 2016/2017 are 1-7 respectively) with port-group fixed effects.

fishing season (e.g. changes in the level of competition over the course of a season in a derby fishery); λ_i are controls for port-group fixed effects that account for time-invariant differences in outcomes across port groups; and $F(\cdot)$ is the logit cumulative distribution function.[7]

We estimate the model parameters using Bernoulli quasi-maximum likelihood (QMLE) methods. We conservatively choose cluster robust standard errors to estimate average effects and robust standard errors to estimate the heterogeneous effects, where clusters are defined as port groups. Specifically, we choose between robust and cluster robust standard errors based on the specification that yields the largest standard errors, meaning the specification that would make it less likely for us to find a statistically significant impact of the HAB events. To aid interpretation, all results are converted to marginal effects, or the change in the response variables y_{it} associated with the HAB events.[8]

We estimate two specifications of equations (1) and (2), i.e. specifications with and without control variables (fixed effects and time trends). Additionally, because we are interested in HAB impacts during two different fishing seasons, the 2015/2016 and the 2016/2017 seasons, we estimate separate models with two different definitions of A_t and A_{it}. We either define A_t as being in the 2015/2016 season or being in the 2016/2017 season. When estimating impacts to the 2015/2016 season, we drop observations from the 2016/2017 season from our model and when estimating impacts to the 2016/2017 season, we drop observations from the 2015/2016 season.

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[7] We test the robustness of our result to controlling for week fixed effects instead of fishing week fixed effects, where week numbers correspond to the number of the calendar week (1-52 or 1-53 in some years). We find that our qualitative results are largely unchanged. See the Supplementary Material for estimation results when controlling for week of the calendar year rather than fishing week.

[8] Primary regression results can be found in the Supplementary Materials.

Our impact estimates assume that the outcome data y_{it} are not trending over time after accounting for our control variables and that autocorrelation is not driving our results (see Bertrand, Duflo, & Mullainathan, 2004).[9] Following Jardine et al. (2014), we examine this assumption by performing several placebo tests. Our placebo tests ask the question: what if we wrongly assumed that the HAB event occurred during a season which did not have a HAB event; would we find an "impact" of this placebo event? If so, the placebo test would suggest that our model results may not provide reliable impact estimates. Specification 2 of Equation (1) is used to estimate the placebo tests, by replacing the A_t dummy variable, which is set equal to one for all observations in the treatment or HAB season, with a dummy variable set equal to one for all observations in a "placebo treatment" season, or a season without a HAB event. We test all placebo seasons for which we have at least one season of data before and after the placebo season.

We note that examining changes to the distribution of revenues is not the same as examining changes to the distribution of profits. Therefore, to interpret our results as impacts to the distribution of profitability one must assume that the HAB event did not differentially impact costs for small and large vessels or that any differential impacts to costs did not outweigh the differential impacts to revenues. Dewees et al. (2004) find that fuel costs comprise a major component of variable costs for Dungeness crab harvesters. Given one of the mechanisms through which we describe the HAB impacting distributional outcomes is through large vessels traveling to exploit distant localized fishing opportunities, it makes sense to assume that fuel costs were also increased for these large vessels. However, it is unlikely that the fishing location choices of large

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[9] While we do not conduct formal tests for autocorrelation, we include a rich set of fixed effects and clustered standard errors when it is conservative to do so. In addition, we use placebo tests to determine whether autocorrelation is driving our results.

vessels were made in such a way that negatively impacted their profitability. Therefore, while we cannot measure profitability directly, it makes sense to assume that revenue and profitability shifted in the same direction.[10]

Finally, we note that, as with any proportion, the proportion of revenue going to small vessels or the proportion of small vessel participation can fall with a decrease in the numerator, an increase in the denominator, or both. We maintain that if the proportion of revenue going to small vessels, or the proportion of small vessel participation, was negatively impacted by the bloom event, then small vessels were harmed relative to a counterfactual where the small vessels were able to maintain their share of the revenue/participation. Thus, even if, during the HAB event, small vessels experienced no change in the level of revenues generated, but large vessels exclusively experienced increased revenue due to the HAB, small vessels suffer from the event because they could not capture their typical proportion of revenue and share in the revenue gains with large vessels. Additionally, modeling proportional outcomes allows us to control for factors that lead to the same proportional changes in outcomes for small and large vessels.[11]

4. Results

Our dataset contains over 1,800 weekly observations of Dungeness crab deliveries for 7 California ports from both the central and northern management districts. Table 1 summarizes revenue and participation, by port group. Mean weekly revenues vary considerably across port groups, e.g. the highest average weekly revenues are generated

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[10] Although a reviewer notes that large vessels may have made unprofitable fishing location choices to retain their crew.

[11] For example, if a 20% increase in the stock of Dungeness crab leads to a 20% increase in revenue for both small and large vessels, we have controlled for the unobserved impact of the stock.

in the San Francisco port group and are nearly 10 times the average weekly revenue for Monterey (Table 1). Mean weekly participation levels are less variable, e.g. San Francisco generates nearly 10 times the mean weekly revenue of Monterey but has less than 4 times the number of vessels participating (Table 1). Table 2 summarizes revenue and participation across vessel size class and small-vessel proportions of revenue and participation, by port group and period, as well as averages across all of the weekly observations. The proportion of revenue to small vessels in the before period varies considerably by port group, with small vessels accounting for the majority of revenue, on average, in Eureka and Monterey, and roughly one third of revenue in Crescent City and Fort Bragg. In all cases, the average proportion of revenue going to small vessels is less than the proportion of small-vessel participation, which is not surprising given differences in vessel capacity. While in some cases the mean weekly proportion of revenue and participation fell in the both HAB seasons, relative to the before period, e.g. Crescent City, Bodega Bay, and Morro Bay, in other cases the proportions remain stable or even increase. We proceed to estimate the impacts of the HAB events on these outcomes after controlling for other factors that impact relative outcomes for small vessels.

Table 1: Summary statistics of weekly data on revenue and participation in fishing seasons 2010/2011-2016/2017

	Mean	Std. Dev.	Median	No. Obs.
Crescent City				
Ex-vessel Revenue	$544,597	$1,269,915	$13,716	198
Participation	29.88	24.43	22.00	198
Eureka				
Ex-vessel Revenue	$438,936	$874,047	$127,250	198

Participation	35.83	24.08	31.00	198
Fort Bragg				
Ex-vessel Revenue	$125,212	$180,048	$53,134	188
Participation	11.69	8.70	10.50	188
Bodega Bay				
Ex-vessel Revenue	$326,163	$550,193	$110,096	212
Participation	30.20	20.93	27.00	212
San Francisco				
Ex-vessel Revenue	$749,552	$1,506,905	$210,599	218
Participation	57.34	42.03	46.00	218
Monterey				
Ex-vessel Revenue	$75,037	$66,859	$54,276	218
Participation	15.38	6.87	14.50	218
Morro Bay				
Ex-vessel Revenue	$99,609	$92,802	$63,839	178
Participation	8.48	4.78	8.00	178

Table 2: Sample means (standard deviations) from weekly data on revenue and participation by vessel class (small and large) and small vessel proportions, by port group and period, and for all observations

	Revenue (10 thousand USD)			Participation (vessels)		
	Small	Large	Proportion	Small	Large	Proportion
Crescent City						
Before period	10.009	43.798	0.322	12.183	16.288	0.496
	(26.726)	(104.809)	(0.268)	(9.140)	(15.196)	(0.207)

2015/2016	10.690	41.638	0.207	16.909	22.636	0.444
	(10.862)	(42.692)	(0.101)	(7.286)	(13.344)	(0.083)
2016/2017	10.365	47.721	0.228	12.912	20.206	0.425
	(22.393)	(110.534)	(0.168)	(10.358)	(18.055)	(0.141)
Eureka						
Before period	18.758	27.209	0.591	22.948	13.182	0.700
	(33.108)	(64.613)	(0.214)	(13.734)	(12.661)	(0.145)
2015/2016	20.614	25.293	0.510	22.545	13.818	0.640
	(20.684)	(25.850)	(0.132)	(7.699)	(7.068)	(0.065)
2016/2017	16.722	16.825	0.622	22.152	12.091	0.707
	(21.934)	(25.515)	(0.218)	(10.450)	(9.655)	(0.139)
Fort Bragg						
Before period	3.158	8.330	0.324	5.262	4.872	0.522
	(6.305)	(12.541)	(0.263)	(4.435)	(3.823)	(0.220)
2015/2016	7.192	11.075	0.364	11.273	5.182	0.669
	(5.253)	(7.897)	(0.155)	(4.714)	(2.272)	(0.091)
2016/2017	6.999	8.766	0.496	10.571	7.536	0.590
	(8.052)	(12.779)	(0.219)	(6.052)	(4.574)	(0.130)
Bodega Bay						
Before period	9.406	23.038	0.410	16.387	13.226	0.591
	(14.731)	(43.626)	(0.204)	(10.358)	(11.016)	(0.145)
2015/2016	11.917	33.067	0.261	16.643	17.429	0.490
	(13.372)	(38.524)	(0.086)	(8.661)	(9.493)	(0.062)
2016/2017	9.004	18.806	0.373	18.500	13.200	0.608
	(13.757)	(27.529)	(0.182)	(12.456)	(10.456)	(0.158)
San Francisco						
Before period	19.201	54.234	0.420	31.806	24.129	0.626
	(33.770)	(122.792)	(0.177)	(20.824)	(22.776)	(0.111)
2015/2016	37.066	80.050	0.446	46.000	31.929	0.623
	(39.259)	(103.223)	(0.186)	(20.917)	(21.255)	(0.086)
2016/2017	20.878	44.318	0.474	34.676	21.206	0.652
	(29.015)	(104.494)	(0.159)	(20.009)	(17.847)	(0.097)
Monterey						
Before period	5.083	2.523	0.670	11.665	3.494	0.773
	(4.837)	(2.556)	(0.212)	(5.585)	(2.113)	(0.111)
2015/2016	10.575	3.553	0.750	17.000	4.643	0.799
	(8.421)	(3.071)	(0.111)	(4.403)	(2.468)	(0.076)
2016/2017	2.894	1.371	0.711	11.176	2.706	0.811
	(1.522)	(1.114)	(0.188)	(4.726)	(1.818)	(0.120)
Morro Bay						
Before period	3.030	6.040	0.443	4.208	3.715	0.582

	(2.405)	(7.435)	(0.293)	(2.141)	(3.240)	(0.228)
2015/2016	5.481	14.590	0.295	5.714	6.643	0.492
	(4.276)	(8.758)	(0.182)	(1.326)	(3.054)	(0.128)
2016/2017	2.518	6.684	0.341	4.500	4.529	0.517
	(1.502)	(6.009)	(0.171)	(1.600)	(2.711)	(0.171)
All observations						
	10.348	24.043	0.455	15.857	11.784	0.615
	(21.921)	(68.977)	(0.257)	(14.629)	(14.254)	(0.188)

4.1 Shifting Deliveries Patterns

Even during the baseline period, large vessels are generally more mobile than small vessels. For example, we identify a subset of large vessels in Crescent City/San Francisco and Eureka/San Francisco homeports, meaning that these vessels are consistently active in two port areas over the course of a single Dungeness crab season, but identify no small vessels exhibiting that spatial landings pattern (Figure 2). The existence of clusters of large vessels active in multiple ports is illustrative of the relative mobility of large vessels.

Analyzing shifts in spatial fishing patterns during the HAB events with heat maps, we see that both small and large vessels shifted their pounds delivered in the two HAB seasons (Figure 2). Furthermore, there are some directional similarities between shifts for small and large vessels. However, the magnitude of the shifts and distance traveled are greater for larger vessels (Figure 2). In the 2015/2016 season, for example, both large and small vessels based out of Eureka shifted landings out of their homeport to San Francisco. Large vessels show a roughly 40% reduction in pounds landed in Eureka and a 33% increase in pounds landed in San Francisco. In contrast, small vessels show a roughly 20% reduction in pounds landed in Eureka and a 16% increase in pounds landed in San Francisco. In the 2016/2017 season vessels based out of Crescent City/San Francisco and Bodega Bay shifted landings out of their homeport of San Francisco and into Crescent City (by roughly 22% and 26% respectively) while smaller vessels based in Bodega Bay, San Francisco, and Monterey all shifted their landings to the closest port to the north (similar to patterns observed for small vessels in the previous season).

4.2 ***Changes in the Proportion of Revenue and Participation for Small Vessels***

As a first step to investigating the impacts on outcomes for small vessels, we estimate Equation (1) without any controls, finding no evidence that, on average across all weekly observations, the HAB events impacted small-vessel revenue or participation proportions (Specification 1, Figure 3). However, after controlling for port-group specific time trends and port group and fishing week fixed effects, we find significant negative impacts to both outcomes (Specification 2, Figure 3). Our estimated marginal effect of the HAB event, on average across all ports, is a reduction in the small-vessel revenue proportion of roughly 0.14 and 0.18 in the 2015/2016 and 2016/2017 seasons respectively and a reduction in the small-vessel participation proportion of roughly 0.07 and 0.12 in the 2015/2016 and 2016/2017 seasons respectively. Therefore, across both seasons, we see that relative revenue to small vessels was more greatly affected by the HAB events than relative small-vessel participation. To put the results into context, the estimated reduction in the proportion of revenue to small vessels during the 2015/2016 season represents a 30% reduction from the before-period mean proportion (0.14/0.455 = 0.3, see Table 2 for the before-period mean).

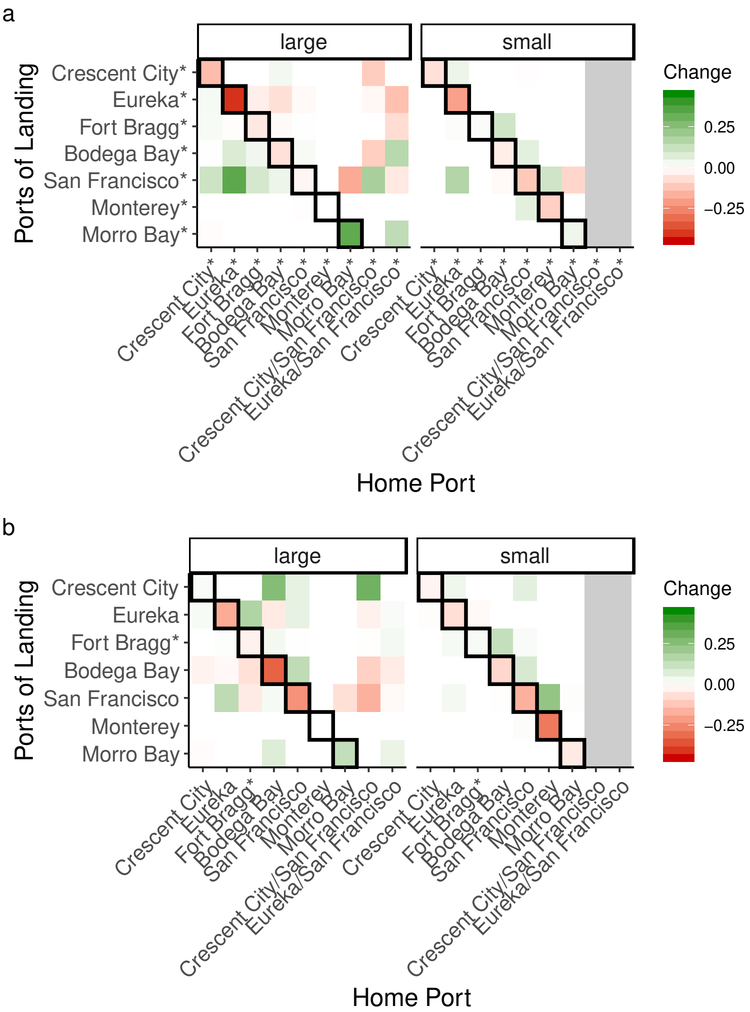

Figure 2: Difference in the proportion of Dungeness crab pounds delivered at each port group between the 2015/2016 season (panel a) or the 2016/2017 season (panel b) and the baseline period (seasons 2011/2012-2013/2014), by homeport groups. Port groups are arranged on the x and y axes in order from north to south and the asterisk (*) denotes a port group protected under the Fair Start Provisions.

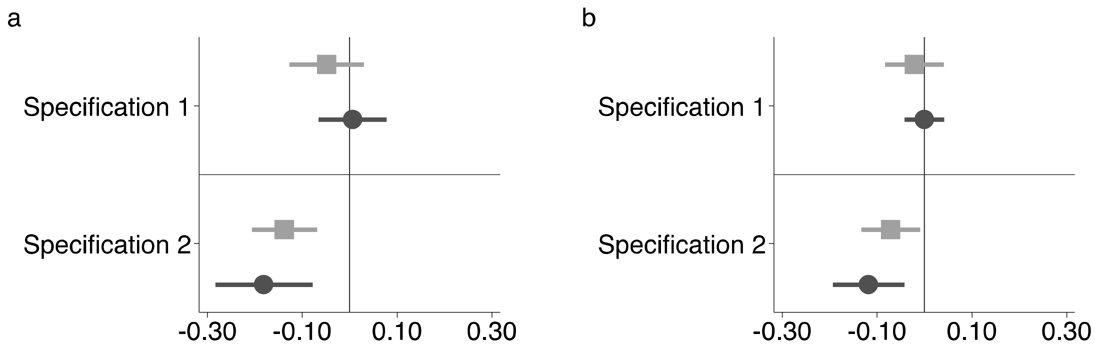

Figure 3: Average marginal impacts of HAB event. The impacts are measured as changes in proportions of: a) of revenue to small vessels and b) of small vessel participation. Square markers represent the 2015/2016 season and circle markers represent the 2016/2017 season.

Estimating heterogeneous impacts, from Equation (2), with the full set of controls, we find small vessels from several port groups were negatively affected (Figure 4). Specifically, impacts to the proportion of small-vessel revenue were negative and statistically significant for Crescent City, Eureka, and Bodega Bay in both HAB seasons and for San Francisco and Monterey in the 2016/2017 season. We find the greatest impacts to the proportion of small-vessel revenue in Crescent City, with impacts over two times the average impact, in both HAB seasons.

In general, as with the average impacts on participation (Figure 3), the impacts to the proportion of small-vessel participation were less in magnitude than impacts to revenue (Figure 4). For example, in the 2016/2017 season, the reduction in the participation proportion for small vessels in the Crescent City area is equal to 63% of the reduction in the proportion of revenue going to small vessels for that port.

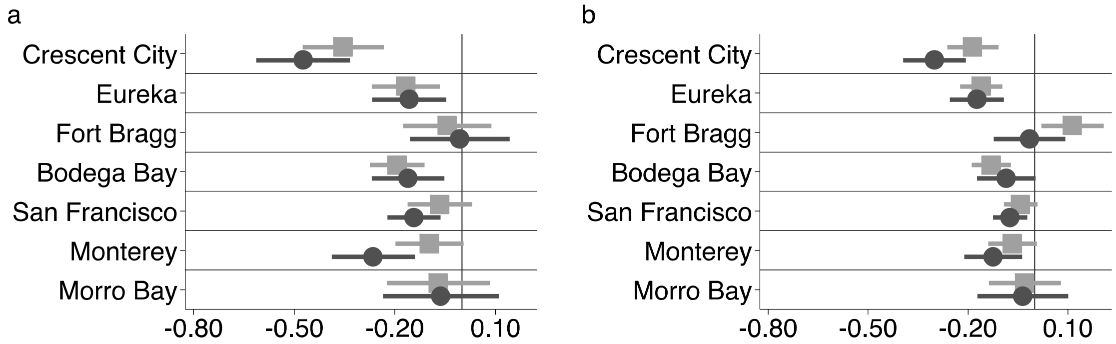

Figure 4: Heterogeneous marginal impacts of HAB event. The impacts are measured as changes in proportions of: a) of revenue to small vessels and b) of small vessel participation. Square markers represent the 2015/2016 season and circle markers represent the 2016/2017 season. Note: port groups are ordered from north to south.

Our placebo tests suggest that our outcome variables are not systematically driven by variables outside of our model in a way that would confound our analysis or by autocorrelated error terms. Figure 5 plots the marginal effects of the HAB event calculated from the estimation of Specification 2 of Equation (1) using dummy variables for placebo HAB seasons in place of dummy variables for the actual HAB seasons. All 95% confidence intervals around the estimated marginal effect of the placebo HAB events include zero.

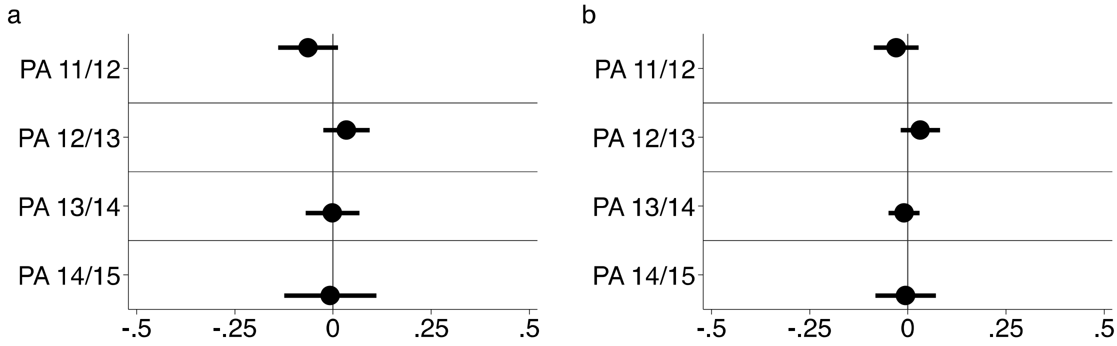

Figure 5: Average marginal impacts of placebo HAB events on the proportion of small vessel revenue (left) and the proportion of small vessel participation (right)

4.3. Synthesis of the results

In the 2015/2016 fishing season we observed substantial shifts in landings by large vessels out of Crescent City and Eureka, the ports with the longest closures (Figure 1). These vessels landed more Dungeness crab in Bodega Bay, San Francisco, and Morro Bay than in previous years (Figure 2). At the same time, during the 2015/2016 season the proportional reductions in revenue to small vessels were greatest in Crescent City, Eureka, and Bodega Bay. This combination of apparently contradictory outcomes — large vessels shifting landings out of some of the ports where small vessels experienced the greatest impact to proportional revenues (i.e. Crescent City and Eureka)—is surprising at first blush. While we cannot state definitively what caused these responses, one potential explanation is that our analysis (Figure 2) misses important intra-seasonal dynamics. For example, roughly half of the large vessels leaving Crescent City during their closed periods and returned once the season was opened. Additionally, these two port groups experienced the longest delays and, thus, greatest seasonal compression, which may have impacted small-vessel outcomes even absent any changes in harvest patterns.

In the 2016/2017 season, by contrast, we observe large shifts out of Bodega Bay, which was the only port in the central district to be delayed in this season. Large vessels left Bodega Bay for distant Crescent City, which then experienced the largest proportional revenue impacts (Figure 4). Small vessels left Bodega Bay for the neighboring port of Fort Bragg. While Fort Bragg experienced the longest delay, we do not see large vessels shifting pounds into Fort Bragg. Instead it is small vessels that appeared to take advantage of the extended and incremental closures in Fort Bragg. This is likely due to the fact that Fort Bragg is a small port in terms of landings (Table 1) and thus not attractive to large vessels.

5. Conclusion

We find evidence that small vessels were disproportionately impacted by the 2014-2016 Northeast Pacific Marine Heatwave that led to a series of HAB events resulting in closures of the Dungeness crab fishery on the U.S. West Coast. Specifically, the HAB events were correlated with shifting spatial fishery landings patterns in California, especially for larger vessels, and a reduction in relative small-vessel revenue and participation. We attribute our findings to the mechanisms of exacerbated seasonal compression in the 2015/2016 Dungeness crab fishing season and localized fisheries closures in both the 2015/2016 and 2016/2017 seasons, which created opportunities for large vessels to participate in distant fishery openings. Our results demonstrate the interconnectedness of fishing ports during a climate shock when mobile vessels can move between ports.

We note Dungeness crab fishers also fish for other species including salmon, albacore tuna, groundfish, and pink shrimp (Dewees et al., 2004; Fuller, Samhouri, Stoll, Levin, & Watson, 2017). Additionally, commercial fishers often earn non-fishing incomes (Holland, Abbott, & Norman, 2019). Understanding the impacts of the HAB events on total revenues to harvesters with diverse fishing/earnings portfolios is another important area for future research that will further illuminate the capacity of fishers to adapt to climate variability and change.

Fisheries managers will likely be faced with growing equity issues due to climate change, in California and beyond. The 2014-2016 Northeast Pacific Marine Heatwave also led to a rise in whale entanglements with Dungeness crab fishing gear, which in 2018 prompted California managers to restrict the summer harvest of Dungeness crab for the first time due to ecosystem considerations, further compressing the fishing season (Santora et al., 2019). With HABs in this region expected to increase in magnitude, frequency, and duration under climate change (McCabe et al., 2016; Trainer et al., 2020), regulatory compression of fishing seasons combined with ecological compression of suitable habitat for Dungeness crab (Chan, Barth, Kroeker, Lubchenco, & Menge, 2019) and protected species (Santora et al., 2019) may amplify these distributional impacts in the coming decades.

While fisheries managers have no control over the need to restrict consumption of Dungeness crabs with high levels of domoic acid or the need to reduce bycatch of protected species, the disproportionate advantages for larger vessels caused by seasonal compression may be mitigated through policy design. For example, since the series of HAB events analyzed here, managers have amended the Fair Start Provisions to increase protections for fishers participating in areas with localized closures. Our results encourage a management focus on both communities-of-place, such as individual ports, but also on communities-of-practice, such as groups of vessels with similar characteristics and constraints, in developing management strategies that allow for adaptation to climate shocks. Future work is needed to develop a deeper understanding of the various mechanistic pathways through which HAB-related closures, and other mitigation measures, impact distributional outcomes in order to better guide the design of policies that can promote equity in fisheries impacted by climate change.

References

Adger, W. N., Huq, S., Brown, K., Conway, D., & Hulme, M. (2003). Adaptation to climate change in the developing world. *Progress in Development Studies*, *3*(3), 179–195.

Backer, L. C., & Moore, S. (2010). Harmful algal blooms: Future threats in a warmer world. *Environmental Pollution and Its Relation to Climate Change; Nemr, A., Ed*, 485–512.

Bauer, M. (2006). *Harmful algal research and response: A human dimensions strategy*.

Berdalet, E., Fleming, L. E., Gowen, R., Davidson, K., Hess, P., Backer, L. C., … Enevoldsen, H. (2016). Marine harmful algal blooms, human health and wellbeing: challenges and opportunities in the 21st century. *Journal of the Marine Biological Association of the United Kingdom*, *96*(1), 61–91.

Bertrand, M., Duflo, E., & Mullainathan, S. (2004). How much should we trust differences-in-differences estimates? *The Quarterly Journal of Economics*, *119*(1), 249–275.

Boncoeur, J., Coglan, L., Le Gallic, B., & Pascoe, S. (2000). On the (ir) relevance of rates of return measures of economic performance to small boats. *Fisheries Research*, *49*(2), 105–115.

Bray, J. R., & Curtis, J. T. (1957). An ordination of the upland forest communities of southern Wisconsin. *Ecological Monographs*, *27*(4), 325–349.

Britten, G. L., Dowd, M., & Worm, B. (2016). Changing recruitment capacity in global fish stocks. *Proceedings of the National Academy of Sciences*, *113*(1), 134–139.

Callahan, M. (2017a). California Dungeness crab 1eet nets $68 million haul, but small boats continue to struggle. In *The Press Democrat*.

Callahan, M. (2017b). *On the North Coast, Dungeness crab season under way*.

Chan, F., Barth, J. A., Kroeker, K. J., Lubchenco, J., & Menge, B. A. (2019). The dynamics and impact of ocean acidification and hypoxia. *Oceanography*, *32*(3), 62–71.

Charles, A. T. (1992). Fishery conflicts: a unified framework. *Marine Policy*, *16*(5), 379–393.

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R. E. G., Zeller, D., & Pauly, D. (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, *16*(1), 24–35.

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social vulnerability to environmental hazards. *Social Science Quarterly*, *84*(2), 242–261.

Dewees, C., Sortais, K., Krachey, M., Hackett, S., Hankin, D., & others. (2004). Racing for crabs…Costs and management options evaluated in Dungeness crab fishery. *California Agriculture*, *58*(4), 186–189.

Erdner, D. L., Dyble, J., Parsons, M. L., Stevens, R. C., Hubbard, K. A., Wrabel, M. L., … Bienfang, P. (2008). Centers for Oceans and Human Health: a unified approach to the challenge of harmful algal blooms. *Environmental Health*, *7*(2), S2. BioMed Central.

Fuller, E. C., Samhouri, J. F., Stoll, J. S., Levin, S. A., & Watson, J. R. (2017). Characterizing fisheries connectivity in marine social–ecological systems. *ICES Journal of Marine Science*, *74*(8), 2087–2096.

Hackett, S. C., Krachey, M. J., Dewees, C. M., Hankin, D. G., & Sortais, K. (2003). An economic overview of Dungeness crab (Cancer magister) processing in California. *California Cooperative Oceanic Fisheries Investigations Reports*, *44*, 86–93.

Hallegatte, S., & Rozenberg, J. (2017). Climate change through a poverty lens. *Nature Climate Change*, *7*(4), 250.

Hallegraeff, G. M. (1993). A review of harmful algal blooms and their apparent global increase. *Phycologia*, *32*(2), 79–99.

Hallegraeff, G. M. (2010). Ocean climate change, phytoplankton community responses, and harmful algal blooms: a formidable predictive challenge 1. *Journal of Phycology*, *46*(2), 220–235.

Hausman, J. A., & Leonard, G. K. (1997). Superstars in the National Basketball Association: Economic value and policy. *Journal of Labor Economics*, *15*(4), 586–624.

Holland, D. S., Abbott, J. K., & Norman, K. E. (2019). Fishing to live or living to fish: Job satisfaction and identity of west coast fishermen. *Ambio*, 1–12.

Holland, D. S., Speir, C., Agar, J., Crosson, S., DePiper, G., Kasperski, S., … Perruso, L. (2017). Impact of catch shares on diversification of fishers’ income and risk. *Proceedings of the National Academy of Sciences*, *114*(35), 9302–9307.

Hollowed, A. B., Barange, M., Beamish, R. J., Brander, K., Cochrane, K., Drinkwater, K., … Ito, S. (2013). Projected impacts of climate change on marine fish and fisheries. *ICES Journal of Marine Science*, *70*(5), 1023–1037.

Jardine, S. L., Lin, C.-Y. C., & Sanchirico, J. N. (2014). Measuring Benefits from a Marketing Cooperative in the {C}opper {R}iver Fishery. *American Journal of Agricultural Economics*, *96*(4), 1084–1101.

Jin, D., Thunberg, E., & Hoagland, P. (2008). Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. *Ocean & Coastal Management*, *51*(5), 420–429.

Kasperski, S., & Holland, D. S. (2013). Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences*, *110*(6), 2076–2081.

Kates, R. W. (2000). Cautionary tales: adaptation and the global poor. *Climatic Change*, *45*(1), 5–17.

Kroetz, K, & Sanchirico, J. N. (2010). Economic insights into the costs of design restrictions in ITQ programs. *RFF Report, Resources for the Future*.

Kroetz, Kailin, Sanchirico, J. N., & Lew, D. K. (2015). Efficiency costs of social objectives in tradable permit programs. *Journal of the Association of Environmental and Resource Economists*, *2*(3), 339–366.

Marques, A., Nunes, M. L., Moore, S. K., & Strom, M. S. (2010). Climate change and seafood safety: Human health implications. *Food Research International*, *43*(7), 1766–1779.

Martin, K. S., & Hall-Arber, M. (2008). The missing layer: Geo-technologies, communities, and implications for marine spatial planning. *Marine Policy*, *32*(5), 779–786.

McCabe, R. M., Hickey, B. M., Kudela, R. M., Lefebvre, K. A., Adams, N. G., Bill, B. D., … Trainer, V. L. (2016). An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, *43*(19).

McCay, B. J. (2004). ITQs and community: an essay on environmental governance. *Agricultural and Resource Economics Review*, *33*(2), 162–170.

McKibben, S. M., Peterson, W., Wood, A. M., Trainer, V. L., Hunter, M., & White, A. E. (2017). Climatic regulation of the neurotoxin domoic acid. *Proceedings of the National Academy of Sciences*, *114*(2), 239–244.

Mendelsohn, R., Dinar, A., & Williams, L. (2006). The distributional impact of climate change on rich and poor countries. *Environment and Development Economics*, *11*(2), 159–178.

Mendelsohn, R., Emanuel, K., Chonabayashi, S., & Bakkensen, L. (2012). The impact of climate change on global tropical cyclone damage. *Nature Climate Change*, *2*(3), 205.

Moore, S. K., Trainer, V. L., Mantua, N. J., Parker, M. S., Laws, E. A., Backer, L. C., & Fleming, L. E. (2008). Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environmental Health*, *7*(2), S4.

Morley, J. W., Selden, R. L., Latour, R. J., Frölicher, T. L., Seagraves, R. J., & Pinsky, M. L. (2018). Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PloS One*, *13*(5), e0196127.

Paavola, J., & Adger, W. N. (2002). Justice and adaptation to climate change. *Tyndall Centre Working Pap*, *23*.

Papke, L. E., & Wooldridge, J. M. (1996). Econometric methods for fractional response variables with an application to 401 (k) plan participation rates. *Journal of Applied Econometrics*, *11*(6), 619–632.

Park, J., Hallegatte, S., Bangalore, M., & Sandhoefner, E. (2015). *Households and heat stress: estimating the distributional consequences of climate change*. The World Bank.

Perry, A. L., Low, P. J., Ellis, J. R., & Reynolds, J. D. (2005). Climate change and distribution shifts in marine fishes. *Science*, *308*(5730), 1912–1915.

Perry, D. (2018). *A Statistical Analysis of the Impacts of Management Decisions on the Distribution of Catch in the California Commercial Dungeness Crab Fishery*.

Pinsky, M. L., & Fogarty, M. (2012). Lagged social-ecological responses to climate and range shifts in fisheries. *Climatic Change*, *115*(3–4), 883–891.

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., & Levin, S. A. (2013). Marine taxa track local climate velocities. *Science*, *341*(6151), 1239–1242.

Porzio, D. (2015). *Review of selected California fisheries for 2014: coastal pelagic finfish, market squid, groundfish, Pacific herring, Dungeness crab, ocean salmon, true smelts, hagfish, and deep water ROV surveys of MPAs and surrounding nearshore habitat*.

Ritzman, J., Brodbeck, A., Brostrom, S., McGrew, S., Dreyer, S., Klinger, T., & Moore, S. K. (2018). Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 US West Coast harmful algal bloom. *Harmful Algae*, *80*, 35–45.

Rosenberg, A. A., Fogarty, M. J., Sissenwine, M. P., Beddington, J. R., & Shepherd, J. G.

(1993). Achieving Sustainable Use of Renewable Resources. *Science*, *262*, 5.

Santora, J. A., Mantua, N. J., Schroeder, I. D., Field, J. C., Hazen, E. L., Bograd, S. J., … Forney, K. A. (2019). Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications*, *In Press*.

Spencer, A. (2014). Crab fleet heads south. *Del Norte Triplicate*.

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., & Herrick, S. (2011). Climate change impacts on the biophysics and economics of world fisheries. *Nature Climate Change*, *1*(9), 449–456.

Tibshirani, R., Walther, G., & Hastie, T. (2001). Estimating the number of clusters in a data set via the gap statistic. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, *63*(2), 411–423.

Trainer, V. L., Moore, S. K., Hallegraeff, G., Kudela, R. M., Clement, A., Mardones, J. I., & Cochlan, W. P. (2020). Pelagic harmful algal blooms and climate change: lessons from nature's experiments with extremes. *Harmful Algae*, *91*, 101591.

Ward Jr, J. H., & Hook, M. E. (1963). Application of an hierarchical grouping procedure to a problem of grouping profiles. *Educational and Psychological Measurement*, *23*(1), 69–81.

Winsemius, H. C., Jongman, B., Veldkamp, T. I. E., Hallegatte, S., Bangalore, M., & Ward, P. J. (2015). *Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts*. The World Bank.

Young, T., Fuller, E. C., Provost, M. M., Coleman, K. E., St. Martin, K., McCay, B. J., … Makino, H. editor: M. (2019). Adaptation strategies of coastal fishing communities as species shift poleward. *ICES Journal of Marine Science*, *76*(1), 93–103.

Supplementary Material

1. Regression results

Tables SM1 and SM2 present estimates obtained from the fractional response models specified in equations 1 and 2 respectively. Using the regression results reported in tables SM1 and SM3 we calculate the marginal effects of the HAB events to generate figures 3 and 4 respectively.

Table SM1: Estimation results from Equation 1 used to create Figure 3

	Revenue proportion				Participation Proportion			
	2015/2016		2016/2017		2015/2016		2016/2017	
HAB impacts:								
Average	-0.195	-0.617**	0.026	-0.803**	-0.090	-0.317*	-0.001	-0.525**
	(0.164)	(0.158)	(0.147)	(0.240)	(0.134)	(0.141)	(0.091)	(0.175)
Time trends:								
Crescent City		0.125**		0.158**		0.0871**		0.133**
		(0.015)		(0.034)		(0.018)		(0.025)
Eureka		0.238**		0.319**		0.154**		0.154**
		(0.014)		(0.036)		(0.015)		(0.025)
Fort Bragg		0.356**		0.230**		0.225**		0.145**
		(0.015)		(0.035)		(0.014)		(0.025)
Bodega Bay		0.193**		0.217**		0.167**		0.165**
		(0.017)		(0.035)		(0.016)		(0.025)
San Francisco		0.354**		0.281**		0.197**		0.188**
		(0.014)		(0.033)		(0.012)		(0.023)
Monterey		-0.0160		0.0501		-0.0114		0.0365
		(0.017)		(0.038)		(0.017)		(0.030)
Morro Bay		0.249**		0.243**		0.126**		0.141**
		(0.015)		(0.035)		(0.015)		(0.025)
Port group fixed effects	No	Yes	No	Yes	No	Yes	No	Yes
Fishing week fixed effects	No	Yes	No	Yes	No	Yes	No	Yes
Observations	1,183	1,183	1,321	1,321	1,183	1,183	1,321	1,321
AIC	1.030	0.932	1.031	0.940	0.946	0.899	0.946	0.900

Note: Asterisk (□) and double asterisk (□□) denote variables significant at 5% and 1% levels respectively. Standard errors are clustered by portgroup and reported in parentheses.

Table SM2: Estimation results from Equation 2 used to create Figure 4

	Revenue proportion				Participation Proportion			
	2015/2016		2016/2017		2015/2016		2016/2017	
HAB impacts:								
Crescent City	-1.174**	-1.592**	-1.051**	-2.113**	-0.697**	-0.829**	-0.776**	-1.343**
	(0.180)	(0.279)	(0.165)	(0.322)	(0.100)	(0.176)	(0.100)	(0.216)
Eureka	0.211	-0.753**	0.670**	-0.703**	0.100	-0.715**	0.405**	-0.774**
	(0.155)	(0.235)	(0.162)	(0.252)	(0.085)	(0.146)	(0.117)	(0.186)
Fort Bragg	-0.386*	-0.198	0.157	-0.0299	0.228	0.508*	-0.112	-0.0672
	(0.195)	(0.302)	(0.166)	(0.339)	(0.121)	(0.213)	(0.103)	(0.246)
Bodega Bay	-0.867**	-0.869**	-0.348*	-0.716**	-0.514**	-0.581**	-0.0365	-0.378
	(0.119)	(0.187)	(0.144)	(0.247)	(0.069)	(0.136)	(0.122)	(0.199)
San Francisco	-0.0446	-0.297	0.0676	-0.638**	0.0272	-0.186	0.155*	-0.327**
	(0.196)	(0.222)	(0.113)	(0.181)	(0.098)	(0.115)	(0.077)	(0.117)
Monterey	1.271**	-0.436	1.073**	-1.181**	0.907**	-0.295	0.984**	-0.554**
	(0.156)	(0.234)	(0.158)	(0.283)	(0.125)	(0.166)	(0.134)	(0.198)
Morro Bay	-0.698**	-0.317	-0.488**	-0.282	-0.505**	-0.131	-0.405**	-0.157
	(0.228)	(0.352)	(0.132)	(0.393)	(0.135)	(0.246)	(0.118)	(0.311)
Time trends:								
Crescent City		0.145**		0.146**		0.111**		0.113**
		(0.046)		(0.045)		(0.034)		(0.0339)
Eureka		0.206**		0.205**		0.0938		0.0917
		(0.070)		(0.0687)		(0.0504)		(0.0494)
Fort Bragg		0.427**		0.425**		0.264**		0.265**
		(0.064)		(0.0653)		(0.0427)		(0.0438)
Bodega Bay		0.204**		0.203**		0.199**		0.200**
		(0.046)		(0.0469)		(0.0322)		(0.0333)
San Francisco		0.338**		0.334**		0.195**		0.192**
		(0.052)		(0.0516)		(0.0340)		(0.0335)
Monterey		-0.0498		-0.0456		-0.0357		-0.0335
		(0.108)		(0.106)		(0.0885)		(0.0869)
Morro Bay		0.221**		0.219**		0.114**		0.113**
		(0.033)		(0.0336)		(0.0203)		(0.0205)
Port group fixed effects	No	Yes	No	Yes	No	Yes	No	Yes
Week fixed effects	No	Yes	No	Yes	No	Yes	No	Yes
Observations	1,183	1,183	1,317	1,317	1,183	1,183	1,317	1,317

AIC	1.031	1.009	1.022	1.006	0.952	0.976	0.945	0.969

Note: Asterisk (□) and double asterisk (□□) denote variables significant at 5% and 1% levels respectively. Robust standard errors in parentheses.

2. Fishing week fixed effects versus week fixed effects

Key model results in figures 3 and 4 depend on estimating equations 1 and 2 using fishing week fixed effects. The variable fishing week is equal to 1 in the first week that a port group is open to fishing, 2 in the second week, and so on. Fishing week fixed effects control for the effects of competition in a derby fishery, where early in the season abundance and competition are high and later on in the season abundance and competition decrease. Here we explore the robustness of our results to replacing fishing week fixed effects in equations 1 and 2 with fixed effects for week of the calendar week (1-52 or 1-53 in some years). Week fixed effects control for seasonal weather patterns that are similar across seasons, the opening of other fisheries that Dungeness crab vessels also participate in, and other factors that may impact the relative success of small vessels that vary by calendar week. Overall, we find our qualitative results are unchanged, but that there are some differences in the magnitude and significance of our impact estimates. Figures SM1 and SM2 are the counterparts to Figure 3 and Figure 4 in the article respectively.

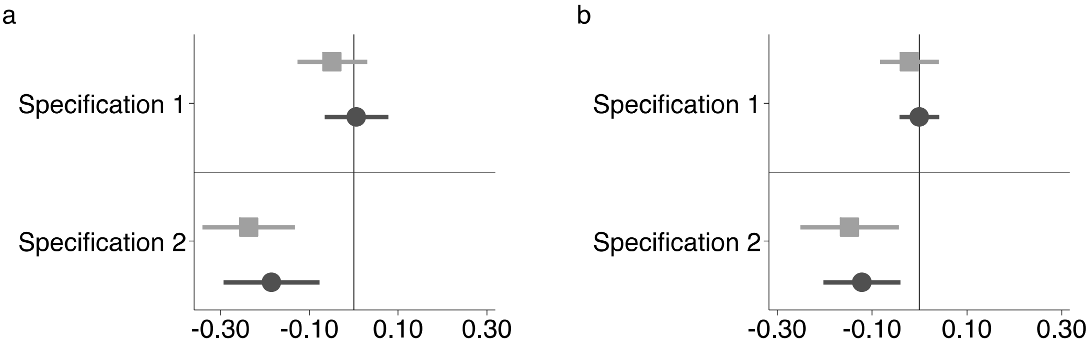

Figure SM1: Average marginal impact of HAB event estimated using week fixed effects. The impacts are measured as changes in proportions of: a) of revenue to small vessels and b) of small vessel participation. Square markers represent the 2015/2016 season and circle markers represent the 2016/2017 season. Note: port groups are ordered from north to south.

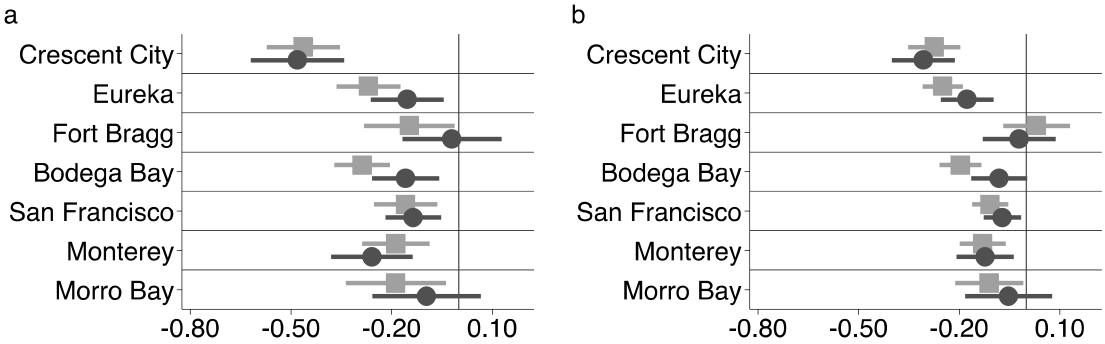

Figure SM2: Heterogeneous marginal impacts of HAB event estimated using fishing week fixed effects. The impacts are measured as changes in proportions of: a) of revenue to small vessels and b) of small vessel participation. Square markers represent the 2015/2016 season and circle markers represent the 2016/2017 season. Note: port groups are ordered from north to south.