Is a Delay a Disaster? Economic Impacts of the Delay of the California Dungeness Crab Fishery due to a Harmful Algal Bloom

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Abstract:

During the 2015/2016 West Coast Dungeness crab (*Metacarcinus magister*) season, the opening of the fishery in California was delayed almost five months due to high and persistent concentrations of domoic acid in crab following a massive coast-wide *Pseudo-nitzschia australis (P. australis)* bloom. A hurdle model was used to estimate lost revenues to fishers due to the delay in the opening of the 2015/2016 season, and an input-output model is used to calculate resulting losses in income and employment statewide. The analysis suggests that Dungeness crab revenue was decreased as a result of the season delay, but the reduction was less than was initially estimated when a request for disaster assistance was submitted. However, the analysis also shows that fishers lost out on revenue from other fisheries equal in magnitude to the reduction in crab revenues because the delayed opening led fishers to reduce effort in non-crab fisheries. The research demonstrates the need to consider impacts beyond the revenue losses to directly affected fisheries. Potential management and industry responses that might mitigate future losses if future large scale *P. australis* blooms threaten fishery delays or closures are discussed along with the research needed to determine whether and how to implement these strategies.

Keywords: Dungeness crab; *Metacarcinus magister*; *Pseudo-nitzschia australis*; economic impacts, fishery

1.0 Introduction

In 2015, the California current experienced a marine heatwave, nicknamed "the blob", with water temperatures more than 2.5 degrees Celsius above normal. The blob led to a number of ecological disruptions including major shifts in the phytoplankton and zooplankton communities at the base of the food web (Bond et al. 2015). It is believed to have triggered a coast-wide bloom of the diatom *Pseudo-nitzschia australis (P. australis)*, which in turn led to high concentrations of the toxin domoic acid (DA) in clams and crabs and forced closures or delays of shellfish and crab fisheries up and down the coast (Du et al. 2016, Zhu et al. 2017, Ritzman et al. 2018). DA outbreaks often continue to impact benthic organisms long after the toxin-producing species have dissipated (Horner et al. 1993, Trainer et al 2007). Documented losses from DA related closings on the West Coast have mainly been in clam fisheries (Dyson and Huppert 2010); however, in 2015/2016 commercial fishery seasons for Dungeness crab (*Metacarcinus magister*) were delayed in all three states. The delay was around a month in Washington and Oregon, but California was delayed up to five months in many areas, not opening until the end of March 2016 (Figure 1). Dungeness crab landings in California for the 2015/2016 season were only 52% of average catches and 58% of average revenue the prior five years, while landings in Washington and Oregon were actually higher than average. There were been additional smaller and shorter DA related closures of Dungeness crab fisheries since 2016, and the frequency, size and intensity of harmful algal blooms along the West Coast is expected to increase in the future as ocean waters warm (Zhu et al. 2017, Trainer et al. 2020). There is a need to develop methods to quantify the economic impacts of HABs of fisheries, both to determine how and to whom to provide assistance and to evaluate ways to avoid or mitigate impacts of future HAB events.

The Dungeness crab fishery is arguably the most important West Coast commercial fishery with gross revenues for California, Oregon and Washington averaging over $200 million annually between 2014 and 2018 and well over 1000 participants. The fishery is managed under a “3S” management scheme, referring to size, sex, and season. Under this management approach, only males with carapace widths ≥159 mm can be landed, and the season is closed in the late summer and fall while crabs are molting and opened only once they have filled out. In addition, all states now have pot limits with multiple tiers, which were introduced in California in 2013-2014, in Oregon in 2006-2007, and in Washington in 1999-2000. Despite limits on permits and pots, the industry catches the vast majority of legal size males each year. Catches in all three states are concentrated in the first six weeks after openings and drop off steeply as the population of legal size males is depleted. The fishery catches an average of 83% of legal size males each year in Northern California and about 65% in Central California (Richerson et al. 2020). Coast-wide, the average exploitation rate of legal size males is 76%.

The Dungeness fishery in California opens as early as mid November in Central California and December 1st in Northern California. Openings are often delayed for a few weeks to allow crab to fill out after molting, but the five month delay in 2015/2016 was unprecedented and led to a request for disaster assistance from the Governor of California. The request, which was submitted before the fishery was actually opened, stated that the delay of the Dungeness crab season had caused an estimated $48.3 million in direct economic impacts[1]. In the United States federal law enables disaster assistance in cases of fishery failures where losses exceed 80% of average revenues in the previous five years, but disasters can be considered in cases of losses between 35% and 80% of average revenues (NOAA 2018). Revenues for the 2015/2016 California Dungeness Crab season were deemed to be sufficiently reduced to qualify as a disaster, and ultimately Congress appropriated over $25 million in disaster aid[2] . However, it was more than three years after the delay that the aid was actually distributed to the affected industry participants (Chambers 2018).

The amount of disaster assistance provided is ultimately a decision of the US Congress, but is typically determined by comparing revenues from the disaster year to average revenues the prior five years. This provides a relatively simple way to estimate the loss in revenues for the disaster year, but it may not be an accurate estimate. In principal the loss should be calculated by comparing actual revenues to what revenues would have been had the event responsible for the fishery disaster (e.g. closure, seasonal delay, etc.) not happened. In this study a statistical model of expected revenue at the vessel level is used to estimate what revenues would have been in the absence of the lengthy delay in the opening of the California Dungeness crab fishery in the 2015/2016 season. The analysis suggests that the lost revenue

[1] Letter from the Governor of California to the Secretary of the US Department of Commerce dated February 9, 2016.
[2] Letter from the Regional Administrator of NOAA Fisheries West Coast Region to the Pacific States Marine Fisheries Commission dated June 21, 2018.

from crab was less than the difference between observed 2015/2016 revenues and the average revenues of the prior five years, in part because fishable biomass had declined which would have reduced revenues anyway. However, it also shows that fishers lost out on revenue from other fisheries because the delayed opening forced many to choose between participation in the lucrative crab fishery when it opened and the other fisheries they would normally have participated in at that time of year. These include salmon, pink shrimp, and tuna fisheries which normally have minimal temporal overlap with the Dungeness crab fishery but have significant overlap in participants (Kasperski and Holland 2013, Richerson and Holland 2017). Lost revenues are estimated at the individual vessel level first, and then economic impacts (e.g. lost income and employment) are calculated for each vessel based on the vessel class before aggregating up to overall impacts. Direct impacts on income and employment are estimated for both the harvest and processing sector as well in indirect and induced impacts throughout the California economy.

2.0 Materials and Methods

A linear Cragg hurdle model (Stata15 TM) is used to predict annual fishing revenues at the vessel level. The model is fit with individual vessel data from the 2009/2010 to 2014/2015 seasons to estimate expected revenue for the 2015/2016 season for vessels that had fished for Dungeness crab in at least one of the five years preceding the closure. A hurdle model jointly estimates the probability of fishing, s_i multiplied by the expected revenue conditional on fishing h_i^*:

$$Y_i = s_i h_i^* \quad (1)$$

where s_i is determined by the participation model: $s_i = \begin{cases} 1 \text{ } if \text{ } z_i\gamma + \epsilon_i > 0 \\ 0 \text{ } otherwise \end{cases}$ (2)

and the latent variable h_i^* is observed if $s_i = 1$: $h_i^* = x_i\beta + v_i$ (3)

Effectively the model is jointly estimating a binary logit model of participation choice s_i (where the dependent variable is 1 if revenue>0 and 0 otherwise) and a linear expected revenue model for observations with positive revenue h_i^* (where the dependent variable is the annual vessel revenue). The dependent variable for the expected revenue model is observed annual vessel revenue calculated from "fish ticket" data maintained by the Pacific Fisheries Information Network (PacFIN). Separate models of total annual revenue from all fisheries and of just Dungeness crab revenue are fit.

Explanatory variables, z_i and x_i, for the participation model and the conditional expected revenue model respectively, include indices of adult male crab abundance at the beginning of the season estimated with a depletion estimator (Richerson et al. 2020). The depletion estimator estimates legal size male biomass by using the trend in commercial catch per unit effort (CPUE) as the stock is depleted to predict the cumulative catch that would occur when CPUE falls to zero. Richerson et al. (2020) estimates fishable biomass for separate areas of the West coast including separate indices for Northern California (N. CA Crab Index) and Central California (C. CA Crab Index). These indices provide a strong indication of potential catch since catch is not limited by a TAC, and the fishery takes an average of 83% of legal size male crab in Northern California and 65% in Central California.

Following Richerson et al. 2018, we include as explanatory variables (in both z_i and x_i): mean revenue for the vessel the prior five years (Mean Revenue); the mean latitude the vessels' crab was landed weighted by revenue (Mean Latitude); the number of years the vessel fished in the prior five years (Years Fished); and an index of diversification of the vessels' revenues (following Kasperski and Holland 2013). The diversification index (HHI) is a Hefindahl index score calculated for each vessel each year that ranges from a high of 10,000 for a vessel that gets all revenue from a single fishery and becomes smaller as revenue is spread across more fisheries (thus a lower HHI indicates a more diversified vessel). The mean percent of the vessels' revenue coming from crab the prior five years (Mean Percent Crab) and the vessels' length are also included as explanatory variables. Mean percent crab is included since it expected that participation probability and revenue will be more impacted for vessels with higher dependence on crab. Vessel length is added as a proxy for fishing power and may also may impact it ability to maintain revenues when conditions vary spatially or there are area closures since larger vessels are generally able to travel further, go on longer trips and fish further from land. Jardine et al. (2020) found evidence that large vessels had a greater ability to mitigate losses from this HAB event. The crab revenue model is similar to the total revenue model but uses crab revenue as the dependent variable and lagged average crab revenues (Mean Crab Revenue) rather than lagged total revenues as an explanatory variable.

The hurdle models is fit with data though the 2014/2015 season to predict vessel level total revenue and Dungeness crab revenue in the 2015/2016 season. The predictions consequently are based on the individual vessel's revenue history, activity and other characteristics in the years preceding the 2015/2016 season (as described in the previous paragraph), and on the estimated crab abundance in the 2015/2016 season from Richerson et al. 2018. To estimate the lost revenues for each vessel the actual observed revenue for each vessel is subtracted from the revenue predicted by the hurdle model. As a sensitivity analysis predictions of revenue are made substituting the average value of the crab abundance indices from the prior five years, since this is a key explanatory variable and one that could have been affected by seasonal shift of the fishery.

The economic impacts of lost revenue are calculated utilizing an input-output model parameterized for West Coast fisheries (Leonard and Watson 2011). Both direct and indirect income and employment impacts are calculated. The direct income and employment impacts include personal income and number of jobs for those directly participating in the fishery (e.g. vessel owners, skippers, crew members, and processing workers). Note that income is not equal to revenue as expenses other than labor are deducted from revenues. Total impacts include indirect effects on sectors that supply goods and services to fishing vessels and induced effects resulting from changes in household spending[3] as the result of a change in income earned among fishing vessels and supporting sectors. Multipliers for the model are specific to the

[3] The effects resulting from a change in household spending are sometimes referred to as the "induced effect."

type of vessel (Table 1). Aggregate revenue losses by type of vessel are first calculated and then impacts are estimated by applying the appropriate multipliers before aggregating up to get total impacts.

3.0 Results

Most, but not all, of the hurdle model explanatory variables are significant for both the total revenue and crab revenue models; however we use the full model for predicton[4]. The hurdle models for expected total revenues (Table 2) and expected Dungeness crab revenues (Table 3) indicate that the index of crab abundance is a strong indicator of both total revenue and crab revenue for the California Dungeness crab fleet. Mean revenue the prior years and the number of years fished are also significant positive predictors of crab and total revenue (revenue models) and of the probability of fishing (selection models). Mean latitude is also significant suggesting higher crab and total revenues in higher latitudes. The percent of revenue coming from crab the prior five years is a significant predictor of total revenue, but not of the probability of fishing. In contrast, the percent of revenue coming from crab is not a significant predictor of crab revenue but is positively correlated with participation in the crab fishery. Diversification has a negative sign in both the total revenue and crab revenue models, suggesting higher predicted revenues with more diversification (i.e. a lower HHI). The sign on HHI is also negative in the selection model indicating a higher probability of participating for more diversified vessels. Vessel length is a positive predictor of both crab and total revenue but is not as a significant predictor of participation.

The hurdle model predictions fit the observations quite well overall, though predictions are biased high for low and zero revenue observations and low for high revenue observations. The hurdle model is a mixed model and there is not a good summary statistic for absolute goodness of fit. An analogue to an R^2 value is calculated as (1- ($SS_{residual}/SS_{total}$)) where SS_{total} is the sum of square differences between observed and mean vessel revenues and $SS_{residual}$ is the sum of squared difference between observed and predicted vessel revenues. Note that, since this is not a linear regression, these summary statistics should not be

[4] Aggregate predictions are very similar with a more parsimonious model.

considered to have the same meaning as a standard R^2 but they provide some indication of model fit to the data. The R^2 analogue values are 0.74 for the total revenue model and 0.40 for the crab revenue model. Plots of predicted vs. observed revenues and of residuals vs. observed revenues are shown in Figure 3. The hurdle model tends to have negative residuals for low values (i.e. it over predicts revenues), particularly when the actual revenue was zero because the vessel did not fish that year. The hurdle model also tends to have positive residuals (under predict) very high revenue levels. However, the model predicts aggregate revenue very accurately. The distribution, mean and median of residuals varies from year to year (Figure 4). Notably, mean residuals for 2015/2016, which are out of sample predictions, are negative on average. This is expected since the model was expected to over predict 2015/2016 revenues since it does not explicitly account for the long season delay which was believed to have substantially reduced revenue.

In aggregate, the total revenue model predicts that total revenue (all species combined) for the California crab fleet for the 2015/2016 season in the absence of the delay in the season opening would have been $26.1 million higher (Table 4). The bulk of this revenue and the loss is attributable to vessels categorized as “Crabbers”, but vessels that mainly fish in other fisheries (e.g. groundfish, salmon, and shrimp) accounted for 38% of the total revenue for the overall crab fleet and 43% of the losses from the season delay. The crab revenue model predicts that in the absence of the season delay, Dungeness crab revenue for the modeled fleet would have been $13.6 million higher. Thus, over half of the estimated loss in total revenues for the California Dungeness crab fleet is attributable to reduced revenues in other fisheries – from vessels that either dropped out of fishing in 2016 all together or reduced their fishing in other fisheries in order to participate in the delayed crab fishery.

The revenue predictions from the model are sensitive to the abundance estimates used to make predictions. As a sensitivity analysis revenue is predicted assuming abundance equal to the mean abundance the prior five years which is substantially higher than the 2015/2016 abundance estimated by

Richerson et al. (2020), particularly for Northern California. With this higher assumed abundance, predicted crab revenues are $91 million which is 80% higher than the base level prediction. Total revenue would be predicted to be $148 million which is 46% higher that predictions using the abundance estimates from Richerson et al. (2020).

The input-output model calculates direct, indirect, and induced income and employment effects of the lost revenue. Direct income losses for the harvest sector are estimated to be $18.12 million, about half of which is associated with Dungeness crab and half with other species (Table 5). Direct income losses for the processing sector are estimated at $3.29 million, again about half from crab and half from other species. Indirect losses (i.e. the multiplier effect through the rest of the California economy) are of similar magnitude to the direct income losses. Note that these are estimates of income loss associated with all species targeted by the crab fleet. Total income losses associated with lost crab revenues are only about half of the total losses. The model also estimates a loss of 492 jobs in the harvest sector and 111 jobs in the processing sector. Again, only about half of these employment losses are associated with reduced crab revenues – the rest are from reductions in revenues of other species. Note that these employment losses are not full time equivalents. They represent lost positions with the same level of activity as typical positions in these sectors. The loss in employment is thus similar to the loss in estimated revenue in percentage terms.

4.0 Discussion

This study suggests that Dungeness crab revenue in California in the 2015/2016 season was reduced by the 5 month delay in the season opening, but the reduction was likely less than the direct revenue losses estimated by comparing actual revenues to the average of the prior five years. This was due in part to reduced abundance of legal size male crab. Dungeness crab landings are tightly coupled with recruitment of legal size males to the fishery, and the index of recruitment suggest the population of legal size males was lower in 2015/2016 relative to prior years, particularly for Northern California, so predicted revenues were lower. While Richerson et al. (2020) provides the best estimate of actual abundance available, it is possible that the depletion estimator provided a negatively biased estimate of abundance in 2015/2016 due to the abnormal timing of the fishery. The estimator uses commercial CPUE data to estimate abundance and if the functional relationship between CPUE and abundance was altered by the time of the fishery it could bias results though how much or in which direction is unclear. If the depletion estimator underestimated crab abundance in 2015/2016 the predicted losses caused by the season delay may have been substantially underestimated by the model as suggested by the sensitivity analysis that sets 2015/2016 abundance equal to mean levels the prior five years. It is also possible that some of the uncaught crab survived and was caught the next season which would offset losses, but it is not known whether crab surviving the first year of exposure to the fishery contribute much to subsequent seasons due to the lack of a formal stock assessment or data on the age structure of catch.

Many West Coast fishers diversify their income by participating in multiple fisheries, which can reduce interannual variability of revenue and financial risk (Kasperski and Holland 2013), but diversification may not offset the losses from a delay or closure unless fishers have access to a good substitute fishery during the closure. Diversification strategies often involve participation in fisheries that occur at different times of years allowing fishers to not only reduce income variability but reduce fixed costs per dollar of revenue by making greater use of their vessel. This diversification strategy may have been less helpful when the crab season was delayed because the delayed season overlapped with other fisheries. Some crabbers did not fish at all in 2016, giving up both crab revenue and revenue from other fisheries. Other crabbers did fish for crab but apparently lost out on revenue from other fisheries that they normally would have participated in during the delayed opening of the crab fishery. This includes salmon, tuna, and shrimp. Most fishers did not have an alternative fishery to participate in during the time the fishery was delayed because nearly all fisheries are limited access and relatively few crabbers had permits for other fisheries occurring in the winter. As a result, the losses to the crab fleet as whole were compounded by losses from other fisheries approximately equal to the lost crab revenue. Some of these revenue losses from crabbers non-participation in other fisheries may have been offset by higher landings for those who did participate in those fisheries; however this is difficult to discern since many of those fisheries are not subject to total catch limits. This illustrates that, to understand the impact of the HAB event, it may be important to consider indirect effects on other fisheries as well.

The economic impacts calculated here were likely a combination of lost harvest and lower prices. Mao and Jardine (2020) estimated that the HAB event in 2015/2016 reduced ex-vessel prices by 22%-23%. They postulate that this reduction may have been due to an expectation by processors that they would be forced to reduce wholesale prices because of lower consumer demand associated with the HAB event which was well publicized. In the end Mao and Jardine (2020) did not identify a reduction in retail prices as a result of the HAB, so some of the losses in revenue to the harvesters may have been offset by higher margins for processors or retailers.

Although the $25 million in disaster assistance that was allocated to California (about $14 million of which went directly to owners of commercial crab permits) appears to have compensated for losses due to the season delay, the assistance was not distributed until three years after the losses were incurred. Long delays in distribution of disaster assistance are increasingly common (Marshall McLean 2018), though this delay was particularly long. This suggests that this type of assistance may not be an effective way to ensure the financial viability of fishers and fishing communities that do not have sufficient resources to weather at least a year of low income. Other approaches such as insurance might be useful, but studies that have looked at insurance for fisheries similar to crop insurance have cast doubt on the viability of this type of insurance (Herrmann et al. 2004; Mumford et al. 2009). When businesses suffer economic injuries from a disaster, the Small Business Administration (SBA) may determine if a disaster declaration is warranted and, if so, can provide “Economic Injury Disaster loans (Upton 2013). For example, when a red tide required closure of the Maine shellfish fishery in 2005, SBA determined a disaster declaration was justified though it is unclear how much lending occurred.

When disaster assistance was eventually distributed to Dungeness crab permit holders, it was done on the basis of permit tiers that regulate the number of pots a vessel can fish which may not have reflected individual losses well. Tier 1 vessels can fish a maximum of 500 traps and trap limits drop by 50 pots with successive tiers to 250 for Tier 6 and then down to 175 for Tier 7. Payout ranged from $42,68 for Tier 1 down to $14,983 for tier 7 which is about $85 per pot.[5] While pot limits reflect fishing capacity and should reflect potential losses to some degree, our analysis suggests that impacts of the seasonal closure were highly variable with some vessels earning higher than predicted revenues though most had reduced revenue. We did not rigorously explore the drivers of heterogeneity in revenue impacts across vessels; however, Jardine et al. (2020) found that smaller vessels were disproportionately impacted by the crab season delay in California. They found that small vessels had a relatively greater reduction in participation rates and accounted for a smaller proportion of crab revenue in the 2015/2016 season relative to the prior three seasons. They attribute this to the greater mobility of larger vessels that were able to take advantage of differing opening dates in different areas. Vessels with higher pot limits tend to be larger, so larger vessels would have tended to get higher disaster assistance payouts though they may have been better able to avoid losses.

The economic impacts quantified in this study are only a part of the overall socioeconomic costs of the 2015 coast-wide bloom of Pseudo-nitzschia australis. A full accounting of impacts would require a much broader study to quantify impacts on other fisheries, particularly recreational and commercial shellfish fisheries that experience DA closures, and related businesses. In a survey of two West Coast communities in California and Washington, Ritzman et al. (2018) found that economic hardships for this coastwide HAB event extended far beyond fishing-related operations to affect other local businesses, particularly the hospitality industry. Our study corroborates this finding showing that indirect and induced losses were about equal to direct income losses for harvesters and processors. There were also emotional and

[5] These are estimated payouts announced by California Department of Fish and Wildlife (https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=168134&inline).

sociocultural impacts on residents of fishing communities up and down the West Coast (Moore et al. 2020). While individuals directly involved in fisheries were more likely to suffer financial impacts from the HAB, Moore et al. (2020) found that over 60% of individuals employed in non-fish jobs also reported experiencing negative impacts in one or more areas (i.e., emotional, financial, sociocultural) and were just as likely to report sociocultural impacts (i.e., cultural connections, community identify, and emotional wellbeing).

It may be possible to implement management strategies that can prevent or mitigate losses associated with future DA outbreaks that would require season delays or closures for Dungeness crab fisheries. Since DA in crab tends to be concentrated in the viscera, eviscerating crab before they are cooked and consumed can make contaminated crab safe to eat as long as toxin levels in the crab meat are safe (<20 ppm). In 2018 and 2019, Oregon initially closed some areas of the coast when elevated level of DA were found in Dungeness crab during the season (above 30 ppm in viscera or 20 ppm in meat), but it reopened areas under regulations requiring crab from these and surrounding areas to be eviscerated (personal communication Troy Buell)[6]. Holding contaminated crabs in tanks and feeding them might be an another effective strategy for mitigation since DA concentrations in crab viscera will decline over time (Lund et al. 1997; Schultz et al. 2013). In a controlled experiment Lund et al. (1997) found that DA concentration dropped 38% in 7 days for crabs that were fed uncontaminated razor clams, by 73% in 14 days and by 89% in 21 days. Both of these mitigation strategies may be more effective with early warnings of HABs and DA contamination which can facilitate more timely adaptive responses to reduce losses (Trainer and Suddleson 2005; Trainer et al. 2016, Jin and Hoagland 2008). HAB monitoring and forecasting tools such as the California-Harmful Algae Risk Mapping Model (C-HARM) and Pacific Northwest HAB Bulletin, could allow more timely and spatially-refined identification of areas of high and low toxin risk and smaller targeted closures.

[6] Although regulations allowed for evisceration before or after cooking, evisceration prior to cooking is recommended since DA is water soluble. https://www.oregon.gov/ODA/programs/FoodSafety/Shellfish/Documents/Evisceration%20FAQ.pdf

While these strategies could potentially reduce losses from future closures they require investments in monitoring, testing, and chain of custody infrastructure to ensure contaminated crab are not sold to the public. While our study suggests that potential losses that could be avoided are substantial, a complete cost benefit analysis should compare these potentially avoided losses to the costs of monitoring and forecasting programs needed to implement finer scale management and support decisions of when and where to open and close areas to fishing under different rules, the costs of the mitigation actions (including increased regulatory costs), and how various mitigation measures may affect product value (e.g. if eviscerating crab reduces the value of the crab). To understand the value of mitigation strategies and the investments that enable them, the probable frequency, size and duration of future HAB events that lead to large scale contamination must also be estimated. Toxic blooms of *P. australis* have been shown to be more likely and larger under warmer ocean conditions leading researchers to hypothesize that these events will become more common along the West Coast in future as a result of climate change (McCabe et al. 2016, McKibben et al. 2017). The potential losses may also be compounded by the need to shorten crab seasons to avoid whale interactions (Santora et. al. 2020). This has become an issue in Oregon and particularly in California which now requires the fishery to close in April, only a few days after the date it finally opened in 2016. This suggests the need to consider and evaluate mitigation options is acute and increasing.

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Figure1: Revenue from Dungeness crab by state and season (November-October)

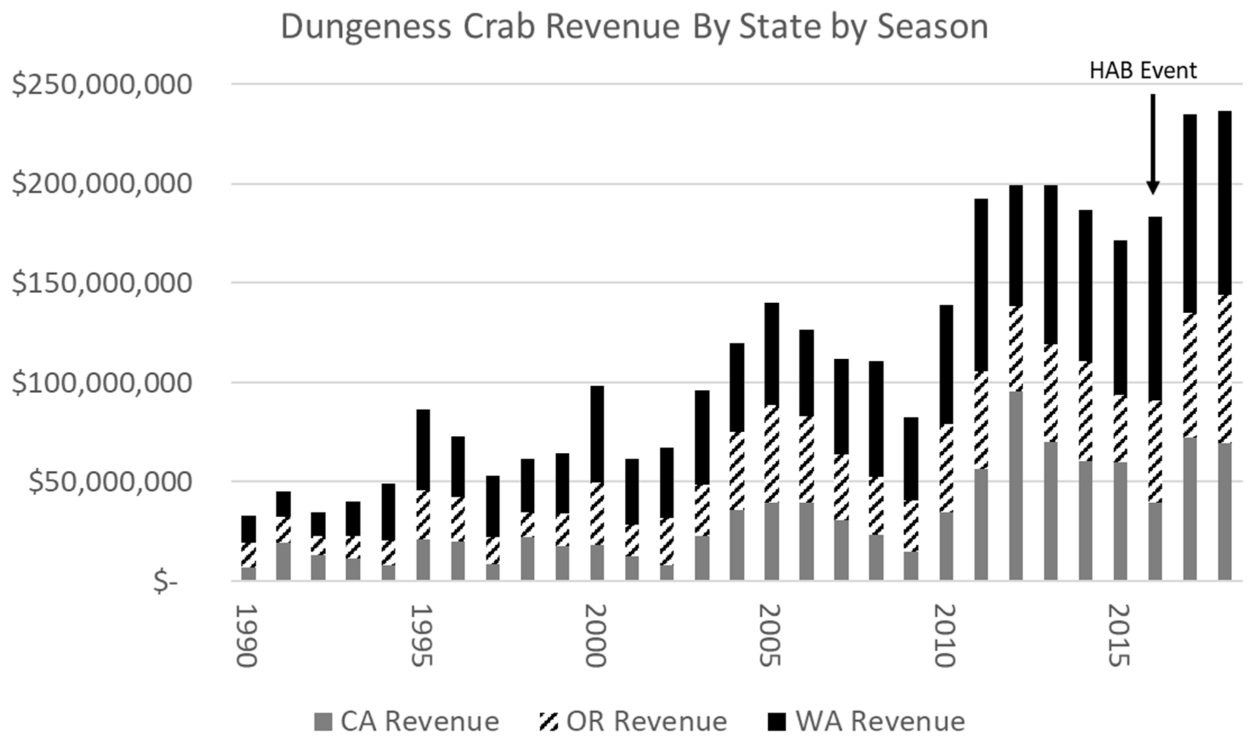

Figure 2: Weekly landings of Dungeness crab in California for the 2011-12 through 2015-16 seasons.

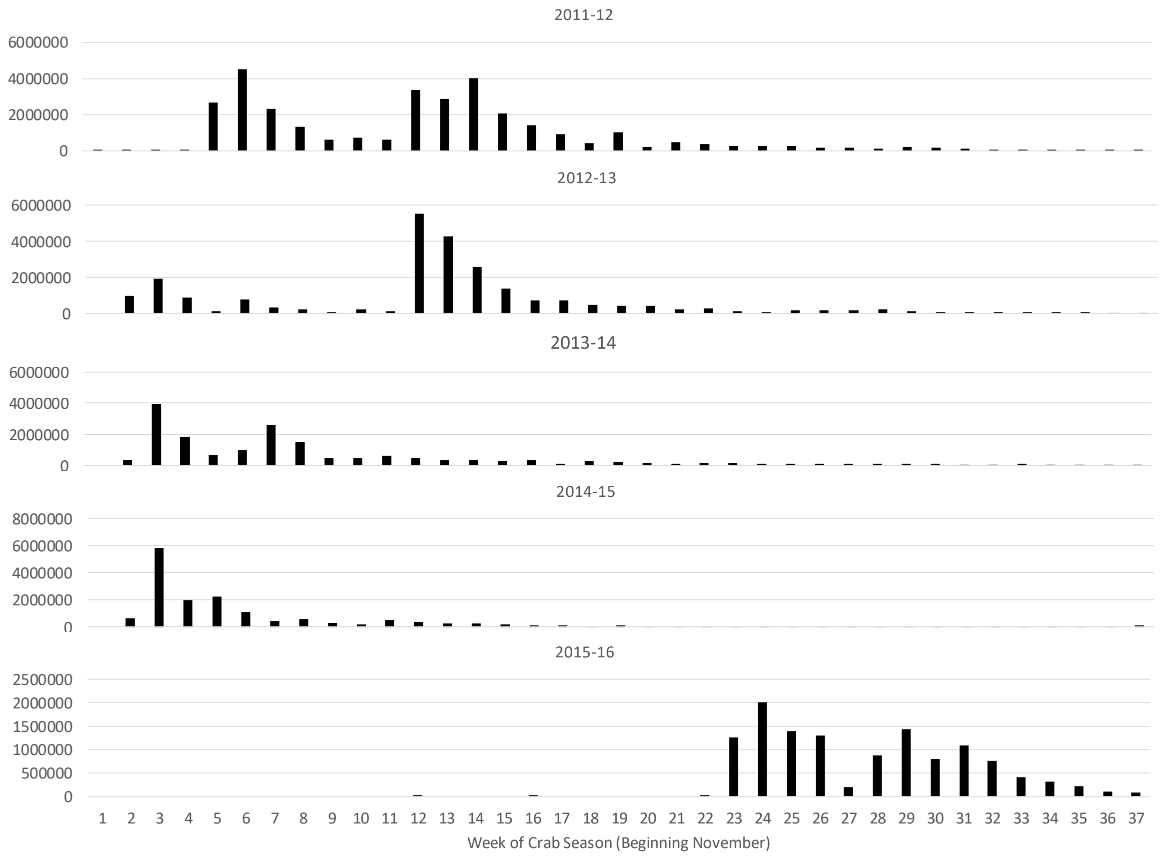

Figure 3: Observed vs. predicted vessel-level total revenue and Dungeness crab revenue

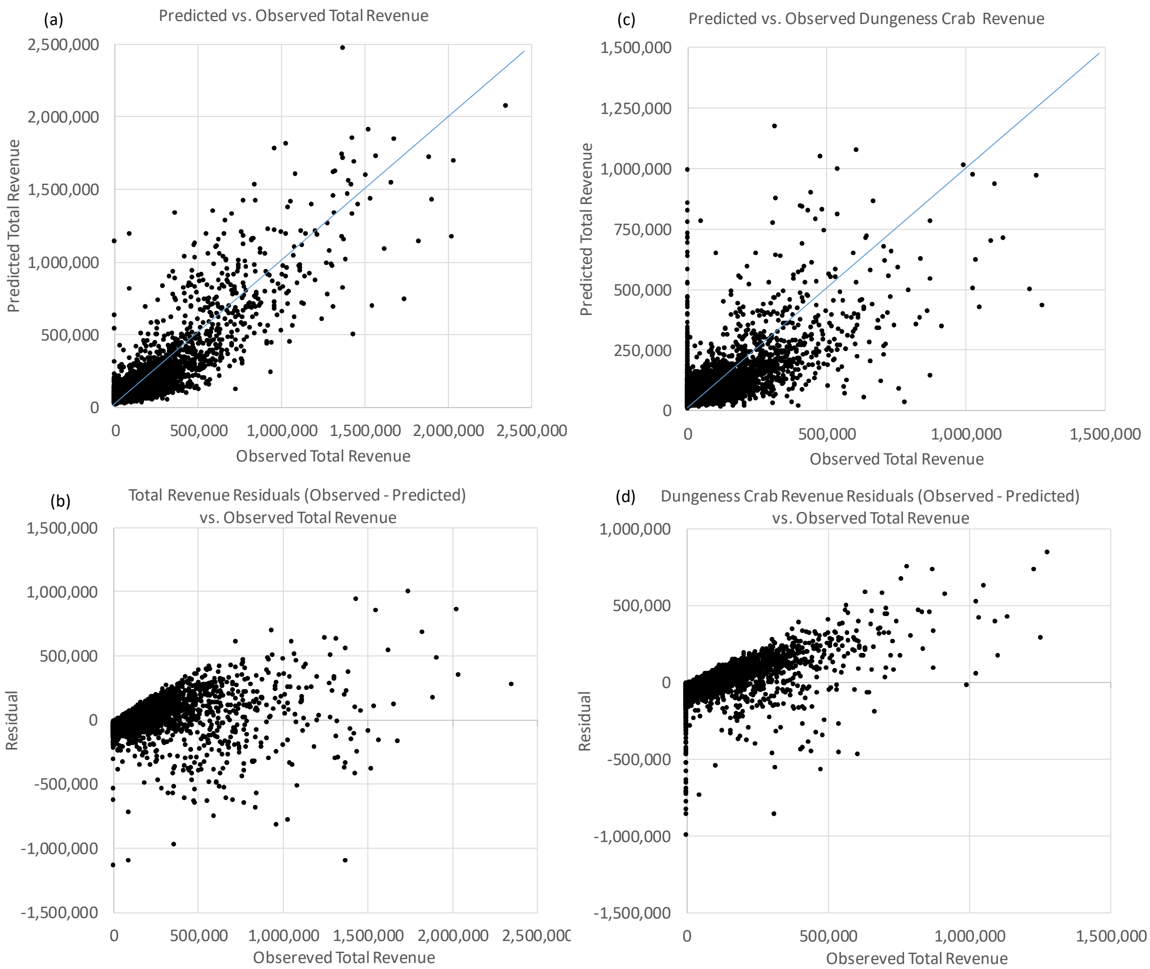

Figure 4: Box plots of residuals by year for predictions of vessel-level total revenue and Dungeness crab revenue. Box plots show mean (x), median, quartiles (box) and 1.5 times the interquartile range (whiskers).

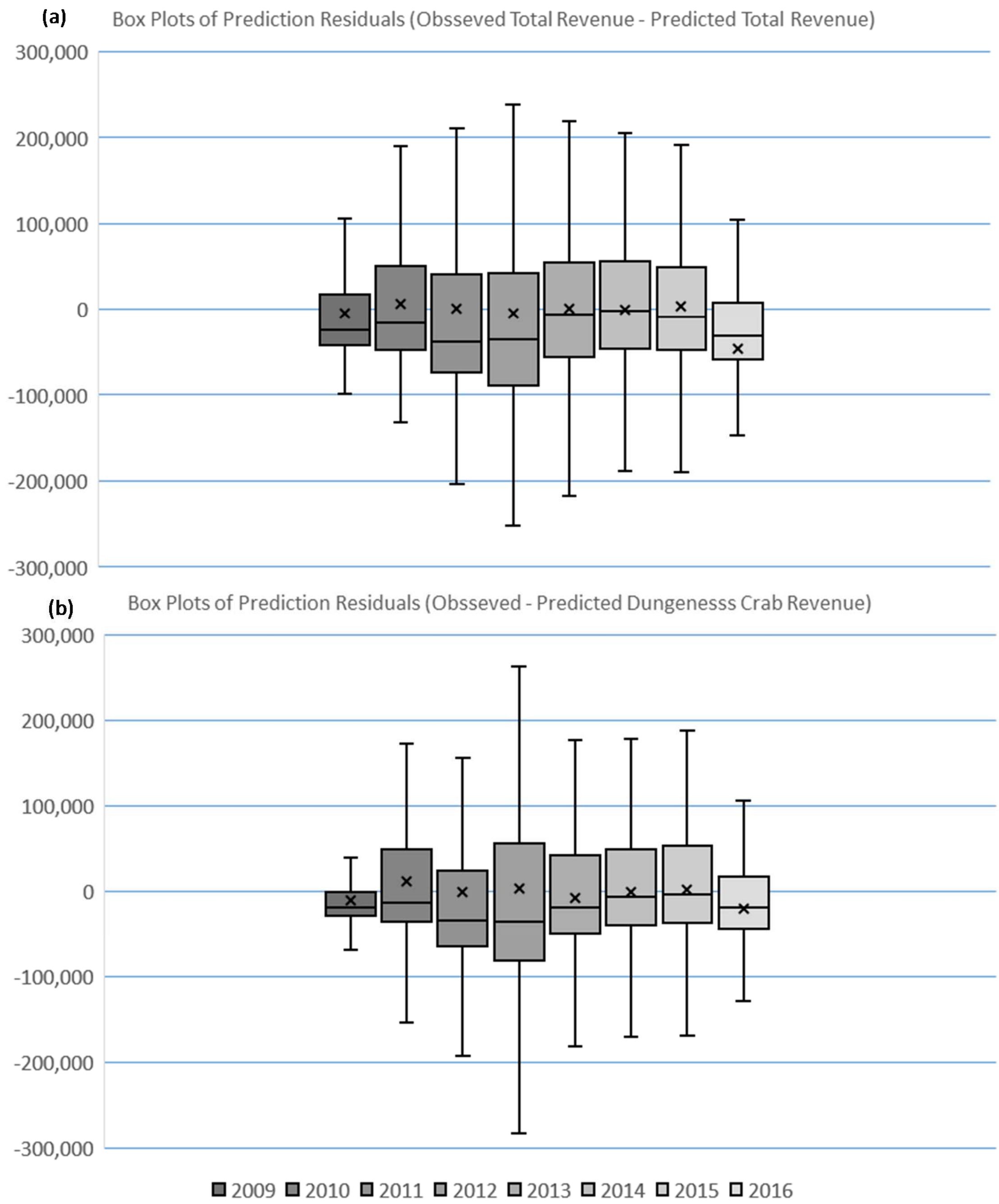

Table 1: Regional impact model multipliers by vessel class for state of California

Vessel Class	Vessel Income Multiplier	Vessel Direct Income Multiplier	Processor Income Multiplier	Processor Direct Income Multiplier	Vessel Employment Multiplier	Processor Employment Multiplier
Alaska fisheries vessel	1.44	0.77	0.24	0.11	0.0000145	0.0000037
Pacific whiting trawler	1.36	0.66	-	-	0.0000109	-
Large groundfish trawler	1.42	0.72	0.66	0.30	0.0000117	0.0000103
Small goundfish trawler	1.34	0.61	0.30	0.14	0.0000627	0.0000047
Sablefish fixed gear	1.40	0.68	0.26	0.12	0.0000144	0.0000041
Other groundfish fixed gear	1.29	0.48	0.26	0.12	0.0000407	0.0000041
Pelagic netter	1.50	0.83	0.23	0.11	0.0000135	0.0000036
Migratory netter	1.41	0.70	0.24	0.11	0.0000660	0.0000038
Migratory liner	1.37	0.67	0.24	0.11	0.0000208	0.0000038
Shrimper	1.39	0.68	0.30	0.14	0.0000125	0.0000047
Crabber	1.41	0.70	0.24	0.11	0.0000209	0.0000038
Salmon troller	1.25	0.45	0.22	0.10	0.0000652	0.0000035
Salmon netter	1.30	0.53	-	-	0.0000667	-
Other netter	1.41	0.70	0.23	0.10	0.0000660	0.0000035
Lobster vessel	1.41	0.70	0.26	0.12	0.0000660	0.0000041
Diver vessel	1.41	0.70	0.26	0.12	0.0000660	0.0000040
Other, more than 15K	1.43	0.73	0.26	0.12	0.0000537	0.0000040
Other, less than 15K	1.07	0.15	0.25	0.12	0.0002573	0.0000039
Charter	0.90	0.35	-	-	0.0000164	-

Table 2: Coefficient estimates from linear Cragg hurdle model of total vessel revenue

Variable	Total Revenue Model		Selection Model	
	Coefficient	P-Value	Coefficient	P-Value
C. CA Crab Index	33,506	0.000	0.0284	0.021
N. CA Crab Index	37,264	0.000	0.0276	0.057
Mean Revenue	1.41	0.000	0.0000	0.000
Mean Latitude	8,140	0.001	-0.0572	0.006
Mean Percent Crab	42,937	0.027	-0.0051	0.973
Years Fished	29,177	0.000	0.2751	0.000
Diversification (HHI)	-9.42	0.004	-0.0001	0.071
Vessel Length	1,613	0.000	0.0001	0.952
Constant	-1,036,694	0.000	2.4060	0.004

Table 3: Coefficient estimates from linear Cragg hurdle model of total vessel revenue from Dungeness crab

Variable	Crab Revenue Model		Selection Model	
	Coefficient	P-Value	Coefficient	P-Value
C. CA Crab Index	42,498	0.000	0.0331	0.000
N. CA Crab Index	43,143	0.000	0.0177	0.098
Mean Crab Revenue	1.60	0.000	0.0000	0.000
Mean Crab Latitude	7,003	0.046	-0.0146	0.442
Mean Percent Crab	26,353	0.306	1.6043	0.000
Years Fished	16,816	0.011	0.2157	0.000
Diversification (HHI)	-13.36	0.001	-0.0001	0.000
Vessel Length	1,648	0.000	-0.0005	0.721
Constant	-1,031,011	0.000	0.2189	0.773

Table 4: Observed, Predicted, and Counter-factual Revenue for the California Dungeness Crab Fleet ($millions)

Vessel Category	All - Total	Crabber	Groundfish Trawlers	Groundfish Fixed Gear	Migratory Liner	Shrimper	Other
Number of Vessels	**557**	453	12	22	20	15	35
Observed 2016 Total Revenue	**$75.8**	$46.9	$6.3	$4.3	$6.6	$7.2	$4.5
Predicted 2016 Total Revenue	**$101.8**	$61.9	$8.3	$5.0	$9.1	$11.5	$6.1
Predicted 2016 Loss in Total Revenue	**$26.1**	$15.0	$1.9	$0.7	$2.5	$4.3	$1.7
Observed 2016 Crab Revenue	**$37.3**	$29.1	$1.4	$1.3	$3.1	$1.3	$1.0
Predicted 2016 Crab Revenue	**$50.8**	$38.9	$2.2	$1.5	$3.4	$3.0	$1.8
Predicted 2016 Loss in Crab Revenue	**$13.6**	$9.8	$0.8	$0.1	$0.4	$1.7	$0.7

Table 5: Economic impacts in California of losses to California Dungeness crab fleet from the 2015/2016 HAB closure ($millions)

Number of Vessels	All Fishing	Crab Fishing
Direct Income Loss - Vessel Operations	$18.12	$9.42
Direct Income Loss - Processor Operations	$3.29	$1.66
Total Direct Income Loss	**$21.41**	**$11.08**
Total Income Loss - Vessel Operations	$36.55	$19.19
Total Income Loss - Processor Operations	$7.14	$3.65
Total Income Loss	**$43.69**	**$22.83**
Employment Loss - Vessel Operations	492	268
Employment Loss - Processor Operations	111	56