Revenue loss due to whale entanglement mitigation and fishery closures

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Abstract

Whale entanglements with fishing gear, exacerbated by changing environmental conditions, pose significant risk to whale populations. Management tools used to reduce entanglement risk, for example temporary area restrictions on fishing, can have negative economic consequences for fishing communities. Balancing whale protection with sustaining productive fisheries is therefore a challenge experienced worldwide. In the California Current Ecosystem, ecosystem indicators have been used to understand the environmental dynamics that lead to increased whale entanglement risk in a lucrative crab fishery. However, an assessment of socio-economic risk for this fishery, as in many other regions, is missing. We estimate retrospectively the losses from ex-vessel revenue experienced by commercial Dungeness crab fishers in California during two seasons subject to whale entanglement mitigation measures. In the 2020 fishing season, our results suggest total revenues would have been $14.4 million higher in the Central Management Area of California in the absence of closures and other disturbances. In the 2019 fishing season, our results suggest ex-vessel revenues would have been $9.4 million higher in the Central Management Area and $0.3 million higher in the Northern Management Area. Our evaluation should motivate the development of strategies which maximize whale protection whilst promoting productive, sustainable and economically-viable fisheries.

Introduction

Conflicts arising from fishery bycatch threaten recovery and conservation of protected species and impacts the socio-economics of coastal fishing communities[1–3]. Globally, entanglements in fishing gear pose significant risk to endangered and threatened whale populations[4–7]. Environmental impacts from climate variability and change have exacerbated whale entanglements in recent years in particular fisheries[8–12]. These entanglements often involve species that are legally protected under the Endangered Species Act or Marine Mammal Protection Act and thus result in temporary fishery closures. In such fisheries, building partnerships between fishery managers and fishing communities is important for reducing both whale entanglement risk and economic impacts of whale protection. Developing mitigation strategies to reduce whale entanglement risk is now a priority of many fixed gear and trap-based fisheries that utilize vertical lines as these gears are most commonly involved in bycatch of whales. Strategies involve using indicators of risk such as metrics of environmental conditions, marine mammal densities and fishery specific metrics, such as monitoring target species and fishing behavior[13,14]. Faced with these challenges, fishery managers often apply mitigation measures that either reduce the number of traps and vertical lines, or set guidelines on opening and closing a fishery to minimize spatiotemporal overlap between peak periods of protected species occurrence in fishing grounds and fishing activities[15–21]. However, development and enactment of risk mitigation of protected species often does not include a risk assessment to assess the economic viability of the fishery facing enhanced mitigation [22].

The California Dungeness crab (*Metacarcinus magister* or *Cancer magister*) pot fishery is one of most lucrative and important fisheries on the US West Coast[23], bringing in more than $80 million in ex-vessel revenues in recent years[24].The California Dungeness crab fishery typically operates from mid-November through mid-July[25], with highest potential conflict with whales in either the season opener or during spring and summer, when whales migrate to and from seasonal foraging and overwintering grounds. Since 2014, the California Dungeness crab fishery recorded a marked increase in the number of reported whale entanglements, mostly involving humpback whales (*Megaptera novaeangliae*), which was attributed primarily to a prolonged marine heatwave and delayed season opener due to contamination of crab from a Harmful Algal Bloom (HAB)[10].

The crab fishery has worked to reduce the number of whale entanglements by developing and applying a Risk Assessment and Mitigation Program (RAMP). The RAMP, informed by the Dungeness crab Fishery Gear Working Group, is composed of crab fishers, resource managers, ENGO members and scientific advisors[26] and is now a legal mandate for managing the fishery[27] (Fig. 1). Starting in the 2018-2019 fishing season, risk mitigation measures are now used to reduce whale entanglements, and have been implemented through either a delayed opening and/or early closure. The RAMP largely focuses on mitigating entanglement risk by monitoring environmental conditions and whale concentrations within management areas. It currently does not include an economic impact risk component nor were socio-economics considered during its development. Humpback whales feeding or travelling along the California coast include individuals from distinct population segments that are federally listed endangered or threatened species and are required to be protected under the Federal Endangered Species Act of 1973. However, under the RAMP, socio-economic impact can be considered (should information be available) if two regulatory actions would equally reduce entanglement risk[27].

Under new RAMP regulations[27], whale entanglement risk is assessed using data on marine life concentrations before the California Dungeness crab fishery opening and continuously until the season ends. Together with increasing whale populations and changing ocean conditions, increased risk of entanglement and more stringent regulations suggest that fishery closures and delays may become more frequent in coming years[10]. Prior to whale entanglement mitigation closures, a multi-month delayed opening caused by a HAB in 2014-2016 caused significant economic impacts to fishers and the wider community, requiring $25 million in federal disaster financial assistance[28–31]. New regulations imposing closures due to whale entanglement risk could bring similarly negative consequences for coastal fishing communities, but these potential losses have not been measured.

The Dungeness crab fishery has long been considered a reliable and economically lucrative fishery for US West Coast fishing communities[32–34]. Populations of Dungeness crab fluctuate markedly from year to year and are driven by density-dependent biological mechanisms as well as exogenous environmental perturbations[35]. Sea surface temperature, sea surface height and upwelling are among ecosystem level physical forces driving Dungeness crab populations, which are common drivers amongst other species in the CCS such as Chinook salmon and Coho salmon populations[36] thus the status of Dungeness crab fishery is linked to the status of other CCS commercial fisheries through their relative responses to common physical drivers. The fishery is also strongly embedded within US West Coast fishery networks, with a high proportion of all fishers gaining revenue from Dungeness crab fishing, whilst also participating in a number of other fisheries[23,37]. Therefore, economic impacts from whale entanglement mitigation could have unforeseen impacts on other fisheries that are linked by cross-participation. Estimating losses resulting from past closures due to whale entanglement risk will benefit ongoing risk mitigation planning, and will help to inform potential impacts of future events.

Our objective is to estimate retrospectively any revenue losses that occurred within recent California Dungeness crab fishing seasons as a result of fishery closures prompted by increased whale entanglement risk. Here, we estimate lost revenues by applying a new economic impacts model designed to measure revenue loss at the individual vessel level, which we then aggregate to the fishery level for two fishing management areas of California. We use hurdle models of crab revenue that estimate both the probability of a vessel participating in the fishery and the expected ex-vessel revenue contingent on participation. Models were fit with historical landings data, from 2011-2018, which included estimates of pre-season Dungeness crab abundance and vessel characteristics including frequency of participation, fishing strategy concentration (as measured by the Herfindahl-Hirschman Index (HHI)), vessel size, latitude of fishing, proportion of revenues from Dungeness Crab and a binary variable indicated whether a vessel switched between management areas within a fishing season. Retrospective loss estimates are determined by comparing observed to predicted revenues at the vessel level for the 2018-2019 and 2019-2020 fishing seasons. With this approach, which assesses the cumulative revenues through the season, we seek to quantify whether delays or closures implemented for whale entanglement regulation affect an overall seasons' revenues. Quantifying the cost of closures will allow socio-economic impact to be considered alongside ecological concerns within the decision making process.

Results

We quantified direct economic impacts arising from delayed opening and early closures prompted by whale entanglement risk mitigation as well as crab meat quality concerns for two fishing seasons (2018–2019 and 2019–2020, subsequently referred to as 2019 and 2020 seasons) in the California Dungeness crab fishery (Fig. 1). Although whale entanglements have declined on the US West Coast since peaking during the large marine heatwave in 2014–2016 (Fig. 1b), several delayed opening and early closures of the fishery were enacted to minimize whale entanglement risk (Fig. 1b). Thus provided a unique opportunity to assess economic impacts in a rapidly changing fishery and management landscape.

Our models incorporated pre-season crab abundance, which was estimated for the two management areas (north management area, NMA; and central management area, CMA; Fig. 2). Pre-season abundance of legal sized male Dungeness crab was estimated at 4.54 and 1.72 thousand tons for the 2019 season and 2.75 and 4.55 thousand tons for the 2020 season for the NMA and CMA respectively (Fig. 2b-c). All covariates except for the mean percent of crab within a vessels total revenues during the baseline period (2011–2018 seasons) had a significant effect ($p < 0.05$) on the selection (participation) model in the NMA. In the CMA, all covariates other than mean latitude of catches had a significant effect on participation (Supplementary Table 1). Fishing strategy concentration (HHI) as well as mean latitude of catches and vessel length had a negative relationship with participation in both regions, suggesting higher probability of participation by vessels with diverse strategies, fishing at lower latitudes within regions and with smaller vessels. (Supplementary Table 1). Mean latitude of crab catches however was not a significant variable in participation in the CMA.

In the revenues model, all covariates other than the mean percent of crab within total vessel revenues were significant for the NMA (Supplementary Table 1). All covariates other than fishing strategy concentration and switching had a positive sign with crab revenues. Participating in fishing in both management areas within a given season has a negative impact on total crab revenues in the NMA. This switching behavior had a negative relationship but statistically non-significant relationship with crab revenues in the CMA. All other covariates were significant in the crab revenues model for the CMA. Of the significant covariates, mean latitude and the diversity index had a negative relationship with crab revenues while all others showed positive relationships with crab revenues. Deviance explained by crab models, calculated using an analogue for R^2, was 0.39 for the NMA model and 0.28 for the CMA model. The model performed well overall at predicting revenues at the fishery level but over-estimated revenues for vessels that did not participate in the two seasons studied and underestimated revenues for some high earning vessels (see Supplementary Fig. 1a-d). Therefore, when presenting revenue losses at the vessel level, we report the 25th -75th percentile of predicted revenues to remove the disproportionate influence of the extremes of the skewed distribution on the average expected losses.

In the CMA, the model predicts that the total crab fishery revenue would have been \$9.4 million higher in the 2019 season and \$14.4 million higher in the 2020 season in the absence of closures (Fig. 3, Table 1). In the NMA, model results suggest that fishery revenues would have been \$0.3 million higher than observed revenues in 2019 and \$3.9 million higher in 2020 (Fig. 3, Table 1). In the 2020 season in the NMA no whale entanglement mitigation was enacted so losses represent other factors influencing revenues such as the impact of Covid-19 on markets (NMFS 2021) [39] .

Table 1
Observed, predicted and loss estimate values (million $) for revenues from the Commercial Dungeness crab fishery in California. N represents the number of vessels included in the analysis.

	2019 season			**2020 season**		
	Observed total fishery revenue	Predicted total fishery revenue	Predicted loss in total fishery revenue	Observed total fishery revenue	Predicted total fishery revenue	Predicted loss in total fishery revenue
Northern Management Area (n = 400)	29.56	29.84	0.28	17.55	21.42	3.87
Central Management Area (n = 525)	15.01	24.38	9.37	24.00	38.43	14.43

At the vessel level in the CMA, based on the 25th to 75th percentile of predicted revenues, the model predicted that vessel level revenues would have been on average $7.8 (SD $39.57) thousand higher in the 2019 season and on average $17.70 (SD $58.04) thousand higher in the 2020 season. At the vessel level in the NMA, based on the 25th to 75th percentile, the model predicted that vessel level revenues would have been on average $1.22 (SD $62.00) thousand higher in the 2019 season and $9.73 (SD $46) thousand higher in the 2020 season.

Given fishery strategy differences between small and large vessels [38] and the large variability in vessel level revenues across the fishery we also investigated losses predicted for small (< 40 ft) and large vessels (> = 40 ft). Median estimated revenue losses were similar between small ($22 thousand in 2019, $14 thousand in 2020) and large ($21 thousand in 2019, $17 thousand in 2020) vessels in the NMA. Predicted losses as a proportion of a vessels mean historical revenues however were higher for small (median of 33% in 2019, and 24% in 2020) than large vessels (median of 19% in 2019, 16% in 2020) (Fig. 4).

In the CMA, revenue losses were larger for large vessels (median of $27 thousand in 2019 and $39 thousand in 2020) than small vessels (median $18 in 2019 thousand and $33 thousand in 2020). As a proportion of a vessels mean historical revenues, small vessels were predicted larger percentage losses (median of 25% and 45% in 2019 and 2020) than large vessels (median of 23% and 37%) (Fig. 4).

Predicted fishery revenues in historical baseline (non-closure) years were on average $0.47 (SD 5.79) million higher for the NMA model and $0.61 (SD 8.35) million higher for the CMA model than observed revenues suggesting some model error or unaccounted for variability. With the exception of 2019 predictions in the NMA, our predictions of losses during closure years are larger than the average model error. This possible error should be considered in the case of small revenue losses (e.g. NMA 2019) and as a proportion of larger predicted revenue losses. Average prediction residuals (observed-predicted revenue) at the vessel level are shown in Supplementary Fig. 1(e-f).

Discussion

Whale entanglements in fishing gear threaten whale populations, seafood production and long-term sustainability of commercial fisheries. While multiple mitigation strategies to reduce entanglements exist, there has been minimal consideration of the economic impact of these strategies. Here, we estimated retrospective losses to ex-vessel revenues for one of California's most lucrative fisheries. Overall, we found fishery closures decreased ex-vessel revenue but regional differences in losses revealed interesting trends in the capacity for the fishery to recoup costs. For example, in the NMA, relatively small losses were predicted ($0.3 million in total) for the 2019 season despite an early closure to the season due to whale entanglement risk.

NMA fishers collectively were able to meet predicted revenue for the season despite a shortening of the fishing 2019 season. In the 2020 season however, the NMA did not experience disturbances due to whale entanglements but larger ex-vessel losses (of $3.9 million) were predicted. This suggests that other disturbances such as a delay to the season due to crab meat quality, lost fishing opportunity related to the COVID-19 pandemic, or other unknown factors, had an influence on ex-vessel revenue during the 2020 season. While most of the 2020 season landings in the NMA occurred before COVID-19 arrived in the US, there is evidence that prices in latter part of the season may have been depressed due to loss of export markets for live crab [39] .

In the CMA however, despite landing the majority of crab available during the 2019 season (see Fig. 2c), losses of $9.4 million were experienced across the fishery. This suggests that the closure to the fishery in the spring may have had some other effect on some other effect on income generation despite catch levels further than reducing total fishery catch (e.g. price, or disproportionate losses by those who would usually fish in the spring). In the 2020 season, whale entanglement risk substantially shortened the fishing season in the CMA, through a delay at the beginning of the season and an early closure in the spring. Estimated losses were largest ($14.4 million) during this season. It is likely that COVID-19 pandemic was also responsible for some of this estimated loss in the CMA in the 2020 season [39] .

Closures and other disturbances appear to have been less impactful in the NMA and high price for Dungeness crab may have contributed to the ability of vessels operating in the NMA to withstand disturbances (Supplementary Fig. 2). Prices were particularly high during the summer portion of the season in 2020 during which time the CMA was closed to Dungeness crab fishing (Supplementary Fig. 2). In previous seasons, e.g. during the HAB of the 2016 season, a shift in demand from closed to open management areas (from California to Washington) for Dungeness Crab has been observed[40]. A similar shift in consumers from the central California region to the Northern California region could explain this increase in price and contribution to revenues in the NMA. This unusual high price late in the 2020 season could also be explained by reopening of industries (e.g. restaurants) that closed early in the COVID-19 pandemic. The NMA did not experience closures due whale entanglement during 2020 and was predicted to have lower than average pre-season abundance (lower catch potential) during 2020 (see Fig. 2.b), while the CMA was predicted to have high catch potential for 2020 (Fig. 2.c).

The CMA also experienced high prices, including decadal high prices for crab during the November-December of the 2019 fishing season (Supplementary Fig. 2). However, losses observed overall across the two seasons suggest the fishery, unlike the NMA, did not get much overall benefit from the high price in 2019 or the high pre-season abundance of crab (i.e. catch potential) estimated for the 2020 season in the CMA. A number of factors may have contributed to a poor season in the CMA including catchability or biology of Dungeness crab as well as external factors such as the COVID-19 pandemic behavioral choice factors (e.g. deciding not to fish)[38]. Temporally shifting or reducing opportunity for participation through closed periods due to whale entanglement risk exacerbated other impacts on revenues in the CMA which were not as impactful on revenues in the NMA.

The high variability in estimated economic impacts per vessel reported here demonstrates that closures did not affect all vessels equally, similarly to impacts observed following a climate related harmful algal bloom in 2015 which were variable by vessel size and between communities[38]. This reflects the diverse nature of the Dungeness Crab fishery in behaviour and fishing strategy and highlights the importance of capturing impacts at finer scales than the fishery level alone. A behavioral choice model, for example one that incorporates location or fishing alternative choice given a closure[41–43] would be a potential method to better understand how spatial management strategies affect fisher behavior and is recommended as a future analysis to assess trade-offs involving socio-economic risk.

Economic cost of mitigation

Many strategies that prevent fishery interactions with marine mammals exist, including gear reductions or modifications, depth limitations and dynamic or seasonal time-area closures[15–21, 44]. In the case of the California Dungeness crab fishery, only two options were enacted in the 2019 and 2020 seasons to mitigate against entanglements of marine life with Dungeness crab gear: delays to the start of the crab season in the winter and early closures in spring due to overlap with whale distribution in fishing grounds. These delays and closures can have differential impacts on the fishery as the fishing season is not heterogeneously prosperous. An example is that closures during the holiday season (Nov-Dec) when Dungeness crab is traditionally consumed can cause substantial lost revenue opportunity for fishers at a time when price and demand is highest[28,40]. Across the fishery, based on observed vessel level revenues during the 2011–2018 baseline period, vessels earned an average of 62.33% (SD 24.04) of annual ex-vessel revenue during the first month of the season (15th Nov-15th Dec for the CMA/ 1st Dec-31st Dec for the NMA). After April 1st, vessels earn on average earn 10.54 % (SD 18.9) of annual ex-vessel revenue. This average, based only on vessels that historically have actively participate past April 1st, (283 vessels in the NMA, 346 vessels in the CMA) rises to 20.36 % (SD 13.3) of ex-vessel revenue. Thus while the majority of the overall fisheries revenue is taken at the start of the season, an April 1st closure could still have a substantial impact on the revenues of active fishing vessels in the spring. The strong seasonal dynamics of the Dungeness crab fishery, largely driven by rapid depletion of legal sized crab, mean that the timing of management actions can have important impacts on fishing revenues. The number of vessels that participate in the spring is larger in the CMA than the NMA and thus could account for some of the difference in impacts observed between the two management areas.

A shift in effort for Dungeness crab fishing due to delays or closures can also impact revenues gained from participating in other fisheries. During the 2015-16 HAB event, estimates of revenue losses by crabbers participating in other fisheries were equal in magnitude to losses estimated from Dungeness crab revenues alone[31]. Timing of closures could have differential impact on vessels with different strategies. For example vessels that target crab throughout the season could be most impacted by early closures in the spring vs diversified vessels missing the window of opportunity for crab at the beginning of the season due to a delay. Determination of economic risk for the fishery, at a minimum, should consider timing of closures in addition to total revenue losses, in order to quantify losses that will be felt at the individual vessel level.

Our analysis does not capture finer temporal scale economic impact further than annual ex-vessel revenue which may have real-time impacts during periods when the fishery is closed, which occur despite delayed revenue accumulation suggesting lower or no overall impact. Closures to the Dungeness crab fishery during 2015-16 caused economic hardship throughout coastal communities, directly impacting the fishing industry, involving processors, market workers and deckhands and also impacting the hospitality, retail and tourism sectors[28–30, 40]. These economic impacts to communities were coupled with welfare issues related to economic loss, stress associated with finding adaptive strategies or employment, as well as cultural identity and removal of social activity within communities[29]. Impacts of lost fishing opportunity also depend on social vulnerability (e.g. levels of poverty, wealth education levels, labor force structure, population composition) and fishery reliance[30]. Socio-economic impacts from whale mitigation measures could permeate into communities further than our analysis (based on ex-vessel revenue only) conveys, and further investigation into these community level impacts is necessary to understand and sustain an equitable fishery supply chain even where there is no absolute revenue loss.

Management Implications

Balancing socio-economic impacts against whale entanglement risk is challenging given the legally protected status of whale populations. However, potential economic losses reported here should motivate the development of mitigation measures (through cooperative innovation between industry, researchers and managers) that allow fishery production to be optimized whilst ensuring successful whale protection. At present, entire management areas, which constitute large regions of the coast, are closed in response to whale entanglement risk in California. Investigating how to minimize the spatiotemporal footprint of closures, such as by defining high risk zones dynamically based on fine-scale information on whale density and fishing effort, could provide an alternative mitigation structure. This could better consider the economic and conservation trade-offs while still being sensitive to changing environmental conditions. The introduction of dynamic zone closures, often broadly referred to as dynamic ocean management, has been demonstrated to reduce risk whilst minimizing lost fishing opportunities[21,45–47], especially when environmental variability is high or species have a dynamic distribution [48] . Moreover, analysis of policy instruments to reduce whale entanglements with the American lobster fishery on the US Northeast coast found that economic costs of risk reduction could be 20% lower when mitigation decisions considered fishing opportunity costs alongside non-monetary benefits (biological risk), compared to non-monetary benefits alone [46] . Dynamic zone closures requires spatially and temporally explicit information on whale density and fishing effort which can be costly to attain. However, revenue losses for Dungeness crab estimated here for the 2019 and 2020 seasons are on a par with losses experienced during the HAB period. During the delays to the 2016 fishing season an estimated $26.1 million was lost from ex-vessel revenues from all species that crab fishers target, including $13.6 million from Dungeness crab alone [31] , requiring $25 million in government aid. Whale mitigation under the RAMP regulation will potentially delay or close the fishery year after year with uncertain economic impact that cannot be sustainably resolved with government aid. Development of tools to mitigate against economic loss while achieving whale protection will be necessary to come to a sustainable solution. This can only be achieved by first including economic loss in risk assessments. Doing so may also provide balance to partnerships between fishery managers and fishers.

In any one season, the Dungeness crab fishery may experience disturbance from crab meat quality delays, HAB related food safety concerns, as well as natural fluctuations in crab availability and catchability. During the 2020 fishing season, disturbances also included the COVID-19 pandemic, which disrupted markets, supply chains and fishing activities. Many of these disturbances are unpredictable and add to the uncertainty of how an additional disturbance due to whale entanglement mitigation might impact the fishery economically. Moreover, in a changing climate, warm ocean conditions expected with higher intensity and frequency[49] as are shifts in whale distributions in response to changing environmental conditions and changing distribution of prey[11]. The legal mandate of a whale entanglement mitigation program will result in future fishery delays and closures, as fishery managers try to prevent another serious spike in entanglements. In this fishery, current triggers to open and close are based on a range of factors, but ultimately depend on the number of whales present within a management region. Currently, a running average of 5 or more humpback whales over a one-week period within a region may cause a closure recommendation by fishery managers[27]. Surveying whale distribution and abundance is difficult because small boat and aerial surveys (considered ideal for a reliable snapshot) are extremely weather dependent. When no whale surveys are conducted a closure may be considered as a precautionary management measure due to unknown risk. Yet, the RAMP process lacks the socio-economic information needed to consider the socio-economic risk to the fishing community. Similarly, if more than one whale is entangled in a season that could trigger a closure of the entire fishing season again with no consideration of the socio-economic risk. Results presented here highlight that the economic effects and risk to fishing communities should be considered when designing whale entanglement mitigation programs. Regulators are obligated to protect Humpback whales, blue whales and Leatherback turtles using the best available science but have a number of regulatory options available to them which include depth restrictions, gear restrictions or modifications and fleet advisories[27]. Having this economic information will facilitate the ability of managers, as set out in the RAMP regulation (subsection d4)[27], to consider the socio-economic impact if deciding between management measures that equivalently reduce entanglement risk.

We have used two fishing seasons as an example of the economic impacts of these new whale entanglement regulations which will be implemented each year going forward. This analysis, along with the community experiences documented following the HAB closures in 2015, provide an example of the economic impact of closures implemented on such spatial and temporal magnitudes. Synthesis of ex-vessel revenues is not a complete picture of the socio-economic impacts of regulations, but it provides a starting point for protecting both whales and fishing communities. While reported whale entanglements remain higher than pre-2014 totals, reported whale entanglements in California have declined markedly in the years following the 2014–2016 large marine heatwave (Fig. 1b). This is a success for this fishery and attributed to increased awareness, development of best practices for fishing gear and the mitigation program to protect whales. We now need to be successful at protecting and mitigating the socio-economic impacts to fishery participants and the fishing communities they support.

Methods

The fishery

The California Dungeness crab fishery is divided into two management areas representing north and central (NMA and CMA, respectively), that have different opening dates. The Commercial Dungeness Crab fishing season typically spans from 1st December until 15th July in the NMA and from 15th November to 30th June in the CMA. The fishing season is named by calendar year in which the season ends (e.g. the 2020 season begins in late 2019 and continues into 2020). Open dates are sometimes adjusted due to crab meat quality, occurrence of harmful algal blooms or due to whale entanglement risk. Season open and close dates for each management area were compiled from online news reports and information provided by CDFW, then cross-checked with landings information following Richerson et al., 2020[50].

The California commercial Dungeness crab fishery has an estimated 501 active participants [51]. The fishery has seen a rise in revenues in the past decade relative to the 2000–2010 period, following a sharp rise relative to the 1970–2000 period. In recent years the Dungeness crab fishery in California has seen annual ex-vessel revenues in excess of $80 million and landings in excess of 12,000 tons[54]. The abundance of pre-season legal size males has also increased greatly in the CMA, with 2000–2016 estimates of abundance averaging nearly five times greater than 1970–2000 estimates [50]. Abundance of pre-season legal size males in the NMA has been relatively stable. The fishery takes on average 83% and

65% of legal sized male crabs each year in the NMA and CMA, with the majority being landed in the first six weeks of the season [50] .

The 2019 season began on time in the CMA on 15 November 2018. However, opening was delayed in the NMA because of crab meat quality (i.e., low weight), and landings began on 22 January 2019. Both management areas were closed to fishing on 15 April due to whale entanglement risk. The season was therefore shortened in the NMA by 53 days (almost 8 weeks) due to a crab meat quality delay and a further 91 days (13 weeks) at the end of the season due to whale entanglement risk. There were additional zone specific delays due to domoic acid presence which delayed fishing up to 55 days at the beginning of the season in the Northern portion of the NMA. In the CMA, the season was shorted by 76 days (11 weeks) due to whale entanglement risk at the end of the 2019 season. The northern portion of the CMA also lost an additional 23 days at the beginning of the 2019 season due to domoic acid presence.

In the 2020 season, the NMA was again delayed due to crab meat quality until 31 December (30 days) but was not closed due to whale entanglement risk in the 2020 season. The CMA experienced both a delay at the beginning of the season until 15th December (30 days) due to persistence of humpback whales and Pacific leatherback turtles on fishing grounds and closed early on 15 May due to entanglement risk, 46 days before the official close date. The season was shortened in the CMA in the 2020 season by 76 days in total.

Fishing and economic data

Data from individual vessel fish tickets (landings records) were provided by the California Department of Fish and Wildlife (CDFW) for all fisheries catches within the years 1981–2020. To include only fishing trips targeting this species, fish tickets recording catches of Dungeness crab were included in the analysis if gear specified “crab or lobster trap” or “entrapping”. Fifty-one duplicate fish tickets were removed and 357, 599 fish tickets reporting catches of Dungeness crab were included. Fish tickets specify the CDFW fishing block area (catch area code) where fishing took place and the port of landing. Fish tickets were assigned to the Northern or Central Management Area by CDFW fishing block (Fig. 2a). If the fishing block recorded spanned both management areas, or if fishing block information was missing, the latitude of the port of landing was used (Fig. 2a). The two management areas are divided at the Sonoma/Mendocino County line (the Central Management Area is < 38.77 ° latitude) (Fig. 2a-c).

All fish tickets recorded in one day by one vessel within one management area were counted as an individual fishing trip. Annual crab revenue per vessel was aggregated from fish tickets by vessel ID. Fish tickets with invalid vessel ID’s were removed prior to analysis. Only fish tickets with landing dates falling within open season dates for each management area were included when calculating within revenues within each respective management area.

Model application

Retrospective crab revenue estimates were calculated using a linear Cragg hurdle model (Stata15 TM)[31]. The hurdle model jointly estimates probability of participation (selection model) in the fishery and multiplies it by estimated revenue (revenues model) to calculate expected revenue per vessel. As per Holland and Leonard (2020)[31], the selection model is a binary logit model of participation choice, while the revenue model is a linear model of annual revenue per vessel. The model was fit with covariates lagged on 7 year rolling averages so that data from the 2004 to 2010 seasons were used to predict revenues in 2011, 2005 to 2011 to predict revenues in 2012 and so on. Revenues from the 2016 season were excluded from the analysis due to closures caused by harmful algal blooms in that season. To predict revenues for the 2019 and 2020 seasons, models therefore used data from the 2011 to 2018 seasons as a baseline period. This baseline period was chosen to represent a range of catches over the recent history of the fishery. We start this time series in the 2011 season because a change point in crab catches occurred during the 2011 season when an increase in the mean level of catches was seen and sustained relative to catches prior to 2011. Vessels that had fished for Dungeness crab in California at least once during the 7 years prior to the closures in the 2019 and 2020 seasons were included. Participation in the fishery, the dependent variable for the binary model, was taken as annual crab revenue > 0. Annual crab revenue per vessel was aggregated from fish tickets as the dependent variable for the crab revenue estimate model. Separate models were run for revenues in the Northern Management Area and Central Management Area of California due to differences in management in the two regions.

Following Holland and Leonard (2020)[31], pre-season abundance estimates of Dungeness crab were included as an explanatory variable in both models. Retrospective abundance estimates using the method from Richerson et al. (2020)[50], updated to the 2019/2020 season, were calculated using a hierarchical linear mixed-effects depletion estimator model. The model uses the trend in catch per unit effort (retained weight per trip) per vessel over the fishing season to estimate the biomass of legal sized male Dungeness crab at the beginning of the fishing season. An index of crab abundance separately for the NMA and CMA for each season was derived from the model (Fig. 2b-c) and included as an explanatory variable in the relevant hurdle model.

As per Holland and Leonard (2020)[31] and Richerson et al (2018)[34] we also included the following variables: the mean annual crab ex-vessel revenue for each vessel, the mean percent of Dungeness crab revenue in a vessels total annual revenue, the number of years a vessel has fished during the rolling baseline period, the mean latitude of catches and vessel length. The Herfindahl-Hirschman Index (HHI) was also included as an index of the vessels' diversification strategy, ranging from 0–1 where 0 is the highest diversity in catches (revenues) and 1 is the least diverse or concentrated (catches of just 1 species). We refer to this as a concentration index. Each of these covariates was based on a lagged 7 year average. An additional variable of "switching" was added to the ex-vessel revenues part of the hurdle model to account for vessels that fish in both management areas in a given season but do not have equal opportunity for fishing in both areas due to fair start rules which require a 30 day waiting period before transiting to land crab in another zone. We included this as a proxy variable of 0 = no switching behavior, 1 = vessel switched between two management areas in that season. Deviance explained by the model was calculated via an analogue to an R^2 value as (1-(SSresidual/SStotal)) where SSresidual is the sum of squared difference between observed and predicted vessel revenues and SStotal is the sum of square differences between observed and mean vessel revenues[31].

To estimate retrospective total fishery revenues that would have been observed in the absence of closures, hurdle models predicted revenues for the 2019 and 2020 seasons for all vessels that participated in the fishery during the 2011–2018 seasons. Values predicted from the hurdle models were aggregated to the sum fishery total for the NMA and CMA. Estimated revenue losses were then calculated by subtracting the observed sum total of revenues for the 2019 and 2020 seasons from the predicted revenues.

Declarations

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Author contributions statement

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Data availability statement

Data from individual vessel fish tickets (landings records) were provided by the California Department of Fish and Wildlife (CDFW). Vessel-level landings data are confidential and the raw data cannot be made public. Data is available by CDFW upon request to CDFW.

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Tables

Table 1. Observed, predicted and loss estimate values (million $) for revenues from the Commercial Dungeness crab fishery in California. N represents the number of vessels included in the analysis.

	2019 season			2020 season		
	Observed total fishery revenue	Predicted total fishery revenue	Predicted loss in total fishery revenue	Observed total fishery revenue	Predicted total fishery revenue	Predicted loss in total fishery revenue
Northern Management Area (n=400)	29.56	29.84	0.28	17.55	21.42	3.87
Central Management Area (n=525)	15.01	24.38	9.37	24.00	38.43	14.43

Figures

Figure 1

Timeline showing a) total monthly ex-vessel revenues from Commercial Dungeness crab fishing in the Northern and Central Management areas of California and b) the number of whale entanglements recorded in California (bars represent the number of reported entanglements of all whale species in each year) and the timeline of biological and management events influencing the fishery. Data points representing less than 3 participants have been removed for confidentiality. This figure was created in R Studio[52].

Figure 2

a) Location of the California Commercial Dungeness crab fishery management areas in the California Current Ecosystem and its location with the USA and estimates of pre-season abundance of legal sized male Dungeness crab by season for b) Northern and c) Central California using a hierarchical depletion estimator model from Richerson et al (2020)[50]. This figure was created in R Studio[52]. Basemap and 200m isobath used the rnaturalearth package (open access).

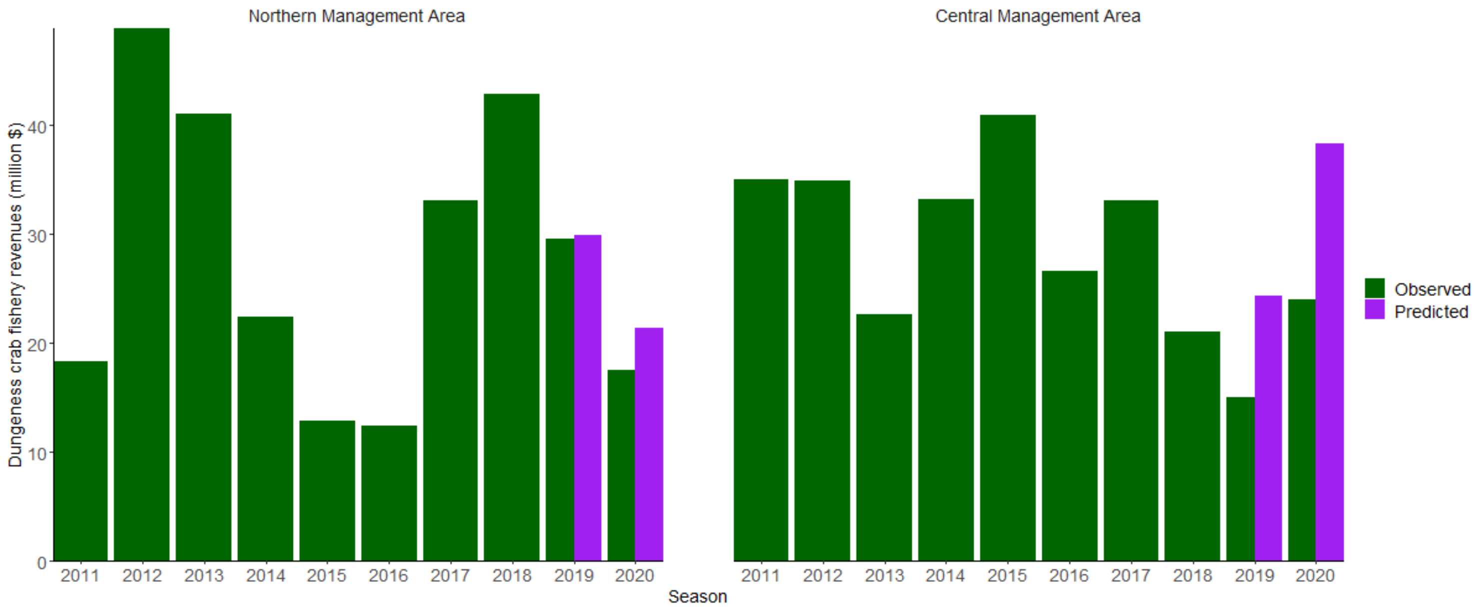

Figure 3

Observed and retrospectively predicted revenues at the fishery level for the Commercial Dungeness crab fishery in California, within the a) Northern and b) Central Management Areas. This figure was created in R Studio[52].

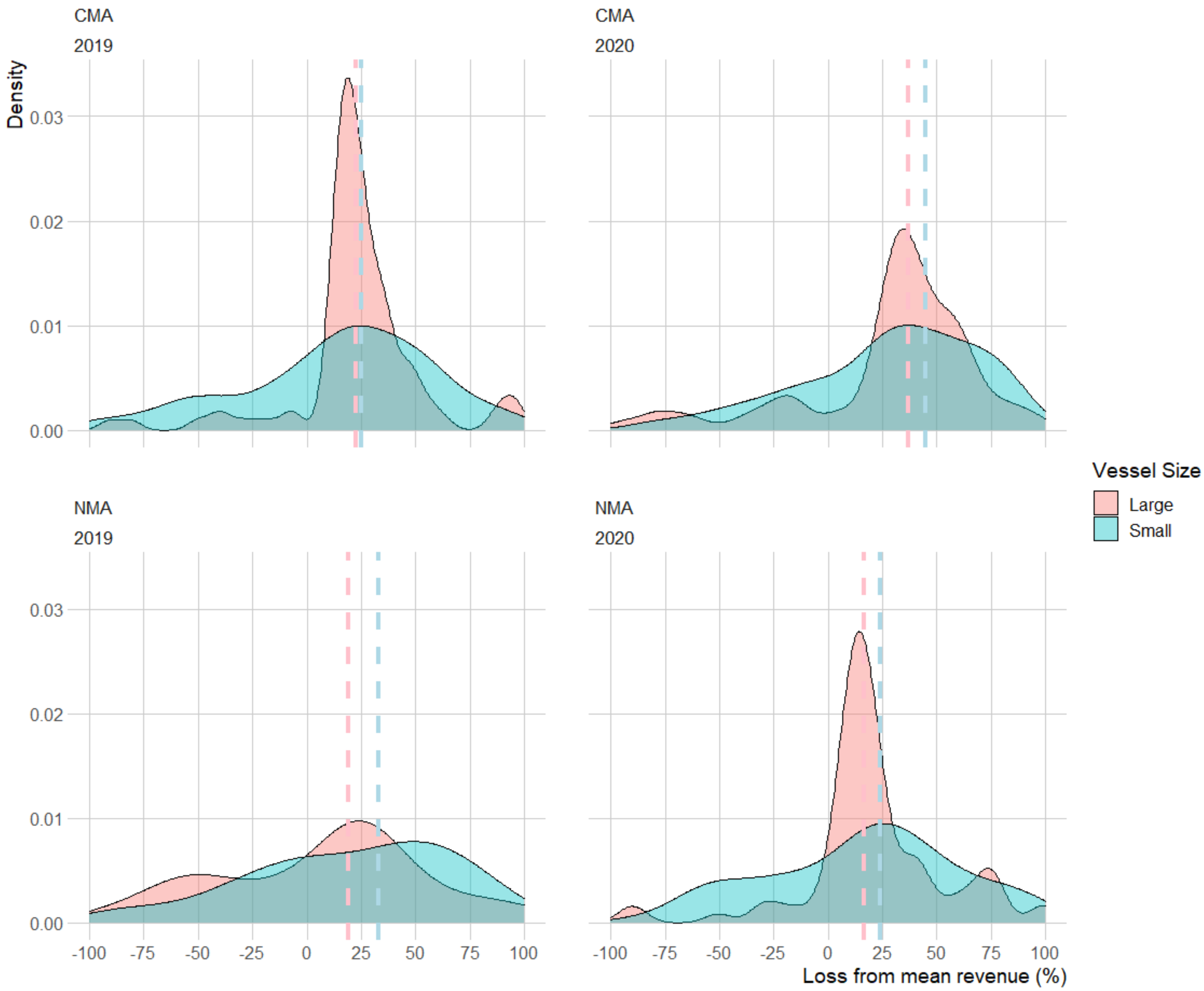

Figure 4

Density plots of estimated percentage ex-vessel revenue loss as a proportion of a vessels mean annual revenue (2011-2018) by small and large vessels in the Northern and Central Management Areas for the 2019 and 2020 fishing seasons. Median revenue losses are shown with dashed lines. Predicted revenues from within the 25th to 75th percentile are included. Negative numbers on the X axis indicate no revenue loss. The X axis has been restricted to between -100-100 for plotting purposes.

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