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Static management presents a simple solution to a dynamic fishery and conservation challenge

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ABSTRACT

Dynamic ocean management, which leverages near real-time data to adaptively shift management in response to changing ocean conditions, is gaining attention as an alternative to static approaches for managing dynamic fisheries challenges. While promising, dynamic management can be data-intensive, costly, and difficult to implement, and its value relative to simpler static approaches should be evaluated before being applied, especially when endangered species and economically crucial fisheries are at risk. Here, we use management strategy evaluation to compare static and dynamic management strategies for reducing humpback whale (*Megaptera novaeangliae*) entanglement risk in the highly lucrative California Dungeness crab (*Metacarcinus magister*) trap fishery. We find that simple gear reductions outperform dynamic management strategies across several measures of performance. Gear reductions maintain uninterrupted fishing seasons and high fisheries catch and effectively prevent whale entanglement risk by directly reducing the number of vertical trap lines. Furthermore, gear reductions are robust to delayed openings resulting from biotoxin contamination and low meat quality, do not depend on the availability or accuracy of entanglement risk indicators, add no new management costs or enforcement challenges, and avoid biases in geographical equity. Dynamic management strategies, which proactively or reactively respond to indicators of entanglement risk, struggle to achieve their intended benefits because they are implemented after long logistical delays and because they redistribute rather than reduce entanglement risk. Bycatch threatens protected species and valuable fisheries around the world and models like the one developed here present valuable tools for weighing solutions to complex fisheries and conservation challenges.

1. Introduction

Climate change is increasing the complexity of already dynamic marine ecosystems and fisheries, spurring interest in dynamic ocean management (DOM) that is responsive to emerging climate challenges (Lewison et al., 2015; Maxwell et al., 2015). In particular, DOM is heralded as an efficient tool for avoiding bycatch of non-target species without compromising target fisheries catches and revenues (Dunn

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et al., 2016). Whereas traditional static approaches schedule and locate management interventions such as fishery closures or gear reductions based on a broad understanding of historical bycatch risk, dynamic approaches trigger targeted management interventions or voluntary avoidance in response to near real-time observations or predictions of contemporary risk (Dunn et al., 2011). While DOM approaches can efficiently avoid bycatch and minimize negative fishery impacts in many contexts (O'Keefe et al., 2014), they can also decrease predictability for fishers and increase information requirements, management costs, and enforcement complexity in other contexts (Lewison et al., 2015).

The stakes for demonstrating the viability and effectiveness of DOM approaches relative to simple static management approaches are elevated when bycatch species are endangered or highly protected. In these cases, the capture of even a few individuals can threaten population health and risk widespread fishery closures. Examples exist in every ocean basin, including sea lions (*Neophoca cinerea*) in Australian shark gillnet fisheries, albatross (*Diomedea amsterdamensis*) in Indian Ocean longline fisheries, and leatherback turtles (*Dermochelys coriacea*) in Pacific Ocean longline fisheries (Lewison et al., 2014). In such cases, regulatory mandates may prevent state-of-the-art dynamic management based on predictive models and/or voluntary avoidance (e.g., Hazen et al., 2018; Howell et al., 2008). Furthermore, enforcement capacity may limit the spatial-temporal scales of realistic dynamic management interventions. For example, highly dynamic hotspot closures (Dunn et al., 2016) may not be feasible under current technological and regulatory regimes. Although the theoretical basis for dynamic management to outperform static management and achieve win-win scenarios for fisheries and conservation is well-documented (Lewison et al., 2015; Maxwell et al., 2015), there is a critical need to evaluate the performance of practical dynamic management strategies under ever changing environmental conditions, especially for protected species incidentally captured in socioeconomically important fisheries.

The California Dungeness crab (*Metacarcinus magister*) fishery presents an instructive and urgent case study for evaluating the ability of feasible dynamic management strategies to maximize the conservation of protected species while minimizing negative impacts to fishing livelihoods. The fishery generates more than $65 million in revenues seasonally (2010–2018 average), supports over 500 vessels, and represents the primary source of revenue for many fishers statewide (Free et al., 2022). However, the fishery is facing significant management challenges as a result of rising entanglements of protected species in the vertical rope lines that connect crab traps with their surface buoys (Saez et al., 2020). In particular, the 2014–2016 marine heatwave known as "the blob" (Bond et al., 2015) precipitated a dramatic spike in humpback whale (*Megaptera novaeangliae*) entanglements (Saez et al., 2020) through a perfect storm of events (Santora et al., 2020). First, elevated biotoxin contamination from a massive harmful algal bloom (McCabe et al., 2016) led the fishery to open five months late, just as whales were returning to foraging grounds during their spring migration. Second, the inshore compression of cool, productive waters further intensified the overlap between foraging whales and the just-opened fishery (Santora et al., 2020). Growing whale populations (Calambokidis and Barlow, 2020), increasing compression of foraging grounds (Santora et al., 2020), and rising harmful algal bloom risk (McKibben et al., 2017) threaten to magnify entanglement risk into the future.

A suite of static and dynamic strategies for managing the fishery in response to entanglement risk have been identified (CDCFGWG, 2017; CDFW, 2021; CDFW, 2020) but their ecological and economic impacts have not been jointly quantified (though see Samhouri et al., 2021 for a retrospective evaluation of a subset of proposed management strategies). Management strategy evaluation, which uses simulation models of key system components (e.g., crab populations, whale populations, fishing fleets, and management) to project fisheries and conservation outcomes under alternative management strategies, represents a powerful tool for measuring and comparing tradeoffs among these potential strategies (Bunnefeld et al., 2011; Punt et al., 2016). While management strategy evaluation has been used to evaluate the ecological and economic impacts of methods for defining and implementing allowable levels of bycatch mortality (Brandon et al., 2017; Punt et al., 2018) and policies for requiring importers to adhere to high bycatch reduction standards (Punt et al., 2020), it has rarely been used to evaluate the consequences of direct bycatch avoidance strategies (Smith et al., 2021).

Here, we use a retrospective management strategy evaluation model to compare the ability for static and dynamic management interventions to minimize entanglement risk while maximizing fishing opportunities in the California Dungeness crab fishery. The model synthesizes diverse historical data and model outputs to simulate the: (i) population dynamics of crabs; (ii) effort dynamics of the fishing fleet; (iii) abundance and distribution of humpback whales; (iv) entanglement of humpback whales in crab fishing gear; and (v) management strategies proposed to mitigate entanglement risk (Figs. 1 & S1; Table S1). Specifically, we consider static strategies that employ statewide season delays, early closures, and gear reductions and dynamic strategies that trigger zonal closures or statewide gear reductions based on either an observed entanglement (*reactive dynamic management*) or observations from a whale abundance survey (*proactive dynamic management*). We measure the performance of management strategies in terms of their ability to prevent entanglement risk, ability to maximize fishing opportunities, and robustness to season delays resulting from biotoxin contamination or low meat quality (Fig. S2 & S3).

2. Methods

2.1. Population dynamics

We modeled the biomass of legal-sized male crabs using a spatial model operating on weekly time steps. We simulated nine recent fishing seasons (2010–11 to 2018–19) where the simulation period for each season is Oct 1 to Jul 30. We used Oct 1 as a start date to allow time for whale abundance surveys before the commercial fishing season opens (Nov 15 and Dec 1 in the Central and Northern regions, respectively; Fig. 1). The 2010–11 to 2016–17 seasons begin with statewide biomass totals equal to historical pre-season legal-sized male crab biomass estimates from Richerson et al. (2020), and the 2017–18 and 2018–19 seasons begin with the mean of these estimates (Fig. S4). We imposed spatial structure according to the California commercial fishing block system, and set the initial distribution of male crab biomass proportional to the mean distribution of catch during the 2013–14 and 2014–15 seasons (Fig. 1 & S5), which did not experience any closures (Fig. S2). We calculated weekly male biomass as a function of natural mortality and fishing mortality:

$$B_{i,t+1} = B_{i,t} * exp\left(-\left(M + \mathrm{F}_{i,t}\right)\right) \tag{1}$$

where $B_{i,\ t+1}$ is biomass in block i in week $t+1$, $B_{i,\ t}$ is biomass in block i in week t, M is natural mortality, and $F_{i,\ t}$ is fishing mortality in block i in week t (Hilborn and Walters, 1992). Natural mortality (M) is 0.6925 yr^{-1} (0.0133 wk.^{-1}) based on Richerson et al. (2020) and block-level fishing mortality ($F_{i,\ t}$) is determined by the fleet dynamics model described below. We did not model recruitment or somatic growth since we used the Richerson et al. (2020) estimates of pre-season biomass to recover the legal-sized male population each season. This assumes that changes in fishing effort have no impact on harvestable biomass. This assumption is supported by studies showing that catch fluctuations are driven more by environmental conditions than by fisheries exploitation (Armstrong et al., 2011; Rasmuson, 2013) and by an analysis of the Richerson et al. (2020) biomass estimates showing that exploitation rate does not have a negative impact on population size in the following year (Fig. S6).

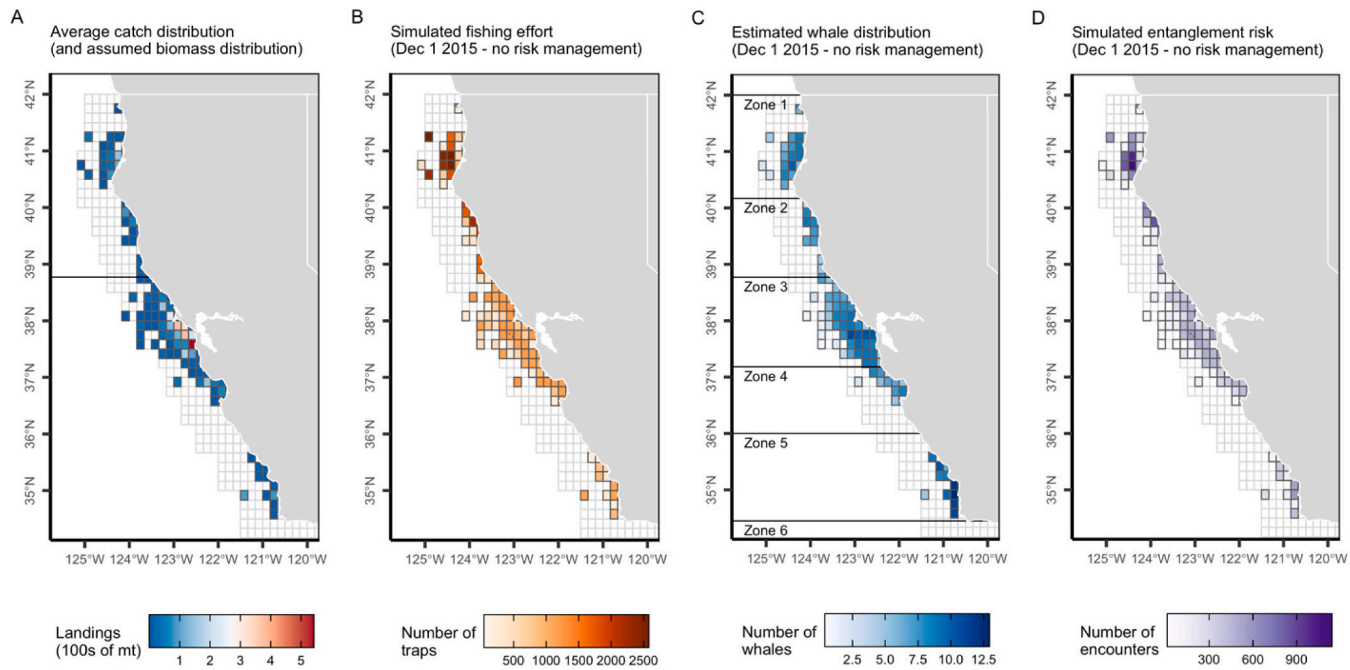

Fig. 1. A conceptual illustration of the spatial simulation sub-models used to simulate (A) population dynamics of Dungeness crab; (B) effort dynamics of the commercial fishing fleet; (C) abundance and distribution of humpback whales; and (D) whale entanglement risk in our management strategy evaluation model. Pre-season legal-sized male biomass is based on Richerson et al. (2020) and is distributed in proportion to the (A) average distribution of catch from the uninterrupted 2013–14 and 2014–15 seasons. Panels B—D illustrate results from an example simulation (Dec 1 2015 in the no risk management scenario). The (B) scale and distribution of weekly fishing effort is set based on available biomass (biomass not in closed areas). The (C) abundance and distribution of humpback whales is estimated by the Forney et al. (in prep) species distribution model. The (D) entanglement risk is measured as the number of likely encounters between whales and traps and entanglements are simulated using probabilities based on estimated historical encounter and entanglement rates. In (A), the solid horizontal line delineates the Northern and Central management regions. In (C), the solid horizontal lines delineate the entanglement risk management zones. Only blocks visited by ≥3 vessels are shown to comply with the rule-of-three.

2.2. Fleet dynamics

We used landings receipts from 2010 to 2018 (9 fishing seasons) to explore the effort dynamics of the California Dungeness crab fleet. The landings receipts report the date of landings, the commercial fishing block where landings were caught, and, since 2013, the permit tier of the vessel (i.e., the maximum number of traps the vessel is permitted to deploy). We used these data to evaluate intra-seasonal patterns in weekly fishing effort in terms of the: (i) amount and proportion of seasonal catch landed each week; (ii) number and proportion of vessels operating each week; (iii) number of traps deployed each week (Fig. S7); and spatial-temporal patterns in the self-reported location of landings (Fig. S8). Landings locations appear reliable given their inter-seasonal consistency (Fig. S8) and logical positioning relative to the port of landing (Fig. S9). To estimate the number of traps deployed each week (which are not recorded on the landings receipts), we assumed that every vessel reporting landings deployed the maximum number of traps allowed by their permit (i.e., Tier 1 = 500 traps, Tier 2 = 450 traps, etc.; Table S2). This necessary simplification implies that we likely overestimate weekly fishing effort, but is identical to the assumptions made by CDFW and the whale entanglement working group (e.g., CDCFGWG, 2020a) up until the 2020–21 season when a biweekly self-reporting requirement was implemented (CDFW, 2020). These explorations revealed biomass-coupled effort dynamics expected for limited-access derby fisheries (i.e., fisheries where a race to fish when the season opens results in a steep and progressive decline in fishing effort and catch) with interruptions resulting from spatial-temporal closures (Fig. S7 & S8).

We reproduced these dynamics using a biomass-coupled effort dynamics model that sets weekly effort based on levels of biomass depletion. We assume that each season opens with 130,000 traps based on the uninterrupted 2013–14 and 2014–15 seasons (Figs. S7 & S10) and that subsequent state-wide fishing effort changes according to the following equation:

$$E_{t+1} = E_t\left(1 + x\left(\frac{B_t}{a^*B_0} - 1\right)\right) \tag{2}$$

where state-wide effort in week $t+1$ (E_{t+1}) is a function of state-wide effort in the previous week (E_t), biomass depletion, and fleet behavior. Whether state-wide effort increases or decreases between weeks is determined by the depletion of biomass in open fishing blocks in week t (B_t) relative to pre-season biomass (B_0), the proportion of pre-season biomass at which bioeconomic equilibrium occurs (a), and the rate at which effort changes in response to changes in biomass (x). See Vasconcellos and Cochrane (2005) for the full derivation of this equation. We assume that state-wide effort is distributed to fishing blocks in proportion to biomass in open fishing blocks (i.e., fishers have perfect knowledge of resource distribution). By making effort responsive to biomass in open fishing blocks, we make effort dynamically responsive to fisheries closures and openings.

We calculated weekly catch resulting from this effort using the Baranov catch equation:

$$C_{i,t} = B_{i,t}^*\frac{F_{i,t}}{M + F_{i,t}}^*\left(1 - exp\left(-\left(M + F_{i,t}\right)\right)\right) \tag{3}$$

where $C_{i,t}$ is the catch in block i in week t, $B_{i,t}$ is the biomass of legal-sized males, $F_{i,t}$ is the fishing mortality rate, and M is the natural mortality rate of legal-sized male crabs (Hilborn and Walters, 1992). The natural mortality rate is 0.6925 yr^{-1} (0.0133 $wk.^{-1}$) based on Richerson et al. (2020). The fishing mortality rate is calculated by multiplying the catchability coefficient (q) by the fishing effort ($E_{i,t}$) derived above.

We estimated values for a (0.8), x (0.1), and q (0.00005) by fitting these equations to the weekly effort and catch dynamics observed during the uninterrupted 2014–15 fishing season through least squares optimization (Fig. S10). These values minimized the joint sum of squared residuals resulting from fits to each time series scaled to its maximum value. We scaled the time series to their maximum values to ensure relatively even weighting in the minimization of their respective residuals (i.e., residuals are similar magnitudes when both time series span 0 to 1). Although the specification of the fleet dynamics model depends on reconstructed effort dynamics, which may be overestimated as a result of the "maximum traps" assumption, we do not expect this assumption to substantively impact our conclusions given the similarity of our reconstruction to those generated by fishery managers (CDCFGWG, 2020a) and researchers using VMS pings as an indicator of fishing effort (Feist et al., 2021).

2.3. Whale distributions and entanglement

We modeled the potential interaction between Dungeness crab fishing gear and humpback whales using the Forney et al. (in prep) humpback whale species distribution model (SDM), which was developed using established and extensively validated methods (Becker et al., 2019; Becker et al., 2016). The model provides bi-daily hindcasts of humpback whale abundance from January 1, 2005 to August 14, 2019 on a 3-km grid that spans all of coastal California (Fig. S11), which we used to hindcast the number and density of whales in each California commercial fishing block over the simulation period (Figs. S11 & S12). We used a two-week rolling average to smooth the bi-daily variability predicted by the model, which generates more realistic results than a weekly average based on the experience of the model developer. The model predicts total humpback whale population sizes (Fig. S12) that are consistent with estimates from the most recent stock assessment for the total CA/OR humpback whale population (Calambokidis and Barlow, 2020).

We estimated the probability that a crab trap encounters a whale using a trap hunting model proposed by Rowcliffe et al. (2003). The model is based on ideal gas theory and the expected rates of contact between randomly moving particles. Briefly, in a time period of length t, a whale swimming at velocity v and at risk of encountering traps within distance D sweeps a strip of water $2Dvt$ in area. Thus, a given density of whales d sweeps strips totaling $2Dvtd$ in area. Assuming that the number of strips that encounter a randomly positioned stationary crab trap follows a Poisson distribution, the probability that a trap in block i encounters a whale (P_i) is equal to:

$$P_i = 1 - exp(-2^*D^*v^*t^*d_i) \quad (4)$$

where the risky passing distance (D) is 13.5 m based on average humpback whale body length (Clapham and Mead, 1999), the mean swim speed (v) is 3.37 km/h (Lagerquist et al., 2008; Mate et al., 1998; Rockwood et al., 2017), the duration of the time step (t) is 1 week (168 h), and the density of whales in block i (d_i) is determined by the species distribution model (Fig. S13). We calculated the number of encounters in a block as the product of the number of traps in the block and the probability that a trap encounters a whale.

Because management is triggered by confirmed entanglements and we lack data on trap encounters and unobserved entanglements, we used the trap encounter probability in Eq. 4 to estimate the probability that an encounter leads to a *confirmed* entanglement (i.e., an observed entanglement that is officially confirmed by the National Oceanic and Atmospheric Association, NOAA). We estimated the probability of a confirmed entanglement by dividing the number of confirmed humpback whale entanglements in California Dungeness crab commercial fishing gear from the 2013–14 to 2018–19 seasons ($n = 43$; Fig. S14; Saez et al., 2020) by the total number of encounters we estimated to have occurred during this time period. Of the 1,692,328 encounters our trap hunting model predicts occurred during the 2013–14 to 2018–19 seasons (Fig. S15; Table S3), we estimate that 0.0025 % of whale-trap encounters lead to a confirmed entanglement. We evaluated the sensitivity of our results to this parameter in a supplemental analysis employing a higher entanglement probability. This probability (0.0065 %) was derived assuming that the 67 confirmed entanglements that could not be linked to a specific fishery (Fig. S15; Table S3) were in fact the result of the commercial California Dungeness crab fishery (i.e., 110 confirmed entanglements/1,692,328 encounters).

We assumed that most confirmed entanglements are observed on delay. We drew the length of this delay from a uniform distribution spanning 0 to 5 weeks based on data on the likely timing of a limited number of entanglements. For 15 of 43 historical humpback whale entanglements, the presence of buoy tags and license numbers off buoys allowed for consultations with gear owners to determine gear set dates, bookending potential entanglement windows (Fig. S16; Saez, unpublished data). We selected a uniform distribution of 0 to 5 weeks because the majority (10 of 15) of these entanglements were observed within 5 weeks of the identified set date; however, this necessary but poorly informed assumption likely underestimates delays, given potential delays of 8–18 weeks for the other 5 entanglements in the dataset and the fact that whale entanglements often go entirely unobserved, as in other trap fisheries (Knowlton et al., 2016; Pace III et al., 2021). We also assumed that management actions in response to a confirmed entanglement are delayed by a minimum of 2 weeks to allow time for the fleet to collect already deployed gear (CDFW, 2020). Put together, we modeled management actions triggered by entanglements as occurring 2 to 7 weeks after the initial entanglement.

2.4. Management strategies

We evaluated the performance of static and dynamic management strategies for mitigating whale entanglement risk based on strategies outlined by CDFW in its entanglement risk management plan, which aims to limit humpback whales entanglements to fewer than nine every three years, approximately a 50 % reduction relative to recent levels (CDFW, 2020). Specifically, we evaluated static strategies that employ season delays (Dec 15), early closures (Apr 1), and gear reductions and dynamic strategies that trigger zonal closures or statewide gear reductions based on either a confirmed entanglement (*reactive management*) or results from a whale abundance survey (*proactive management*) (Table S1). We evaluated static statewide gear reduction scenarios ranging from a fully open (0 % of gear eliminated) to a fully closed fishery (100 % of gear eliminated); however, we focused primarily on the 10 %, 30 %, and 50 % reduction scenarios to illustrate tradeoffs over realistic gear reduction percentages.

Dynamic management strategies employing zonal closures were assessed using (i) the five risk management zones used to monitor and mitigate humpback whale entanglement risk in the Dungeness crab fishery (Fig. 1) and (ii) the ten risk management zones produced by halving these zones (Fig. S17). Reactive management is triggered by a confirmed entanglement. Proactive management follows the schedule of the current management plan: surveys conducted on two-week intervals beginning before Nov 1 inform the opening of the fishery between Nov 15-Dec 31 and monthly surveys conducted beginning before Mar 1 can trigger closures from Mar 15-Jul 15. In the model, the actual survey dates are randomized by $\pm$3 days in the fall and $\pm$ 7 days in the spring to mimic the potential impact of variable weather conditions. We opted not to evaluate the abundance thresholds specified in the current management plan, which we interpret to trigger management action in a zone when fishing grounds (waters $<$100 fathoms deep) have $\geq$20 whales in the fall or $\geq$ 10 whales in the spring. Explorations of the species distribution model output indicate that these thresholds are nearly always exceeded (Fig. S18). Alternatively, these thresholds could be interpreted as applying to a survey, but the absence of a specific and consistent survey design renders fixed abundance thresholds nonsensical. Instead, we triggered management action based on density thresholds (Fig. S19) representing the 50th (0.020 whales/km^2), 70th (0.025 whales/km^2), 80th (0.030 whales/km^2), and 90th (0.035 whales/km^2) percentiles of whale density within zonal fishing grounds (<100 fathoms deep; Fig. S11). Our simulated surveys represent a best case scenario: surveys are conducted on schedule, in every zone, and without error.

2.5. Performance metrics and robustness checks

We measured the performance of each management strategy relative to a "no risk management" scenario using three metrics: (i) proportion of catch landed; (ii) proportion of block-weeks open; and (iii) proportion of whale-trap encounters prevented (Table S4). While revenues may be a better indicator of fisheries performance than catch, we were unable to model ex-vessel price, which depends on complex market dynamics (Mao and Jardine, 2020). Fortunately, high correlation between fleet-wide revenues and catches suggests that foregone landings is a useful indicator of economic performance (Fig. S20). We evaluated the proportion of whale-trap encounters prevented, rather than the total number of entanglements or the proportion of entanglements prevented, because encounter rates directly underpin entanglement rates and are modeled with greater certainty than entanglement rates, which are highly stochastic and uncertain. For this reason, and because management strategy evaluation models are best suited for evaluating the relative rather than the absolute performance of alternative management strategies (Punt et al., 2016), we could not directly assess performance against policy goals to limit entanglements to fewer than nine humpback whales every three years (CDFW, 2021; CDFW, 2020).

The static management strategies are deterministic and were only run for a single iteration. The dynamic management strategies are stochastic due to their dependence on entanglements, which are randomized in when they occur and are observed, and on whale surveys, which are randomized in their timing; thus, we simulated the dynamic strategies for 50 iterations and averaged their performance metrics. Additionally, we evaluated the robustness of the management strategies to season delays resulting from low meat quality and/or high biotoxin contamination by simulating each season using four historical delay timelines (Fig. S2): 2011–12 (identical to the 2012–13 and 2017–18 season delays), 2015–16, 2016–17, and 2018–19 (excluding the early closure) (Fig. S3). The static management strategies were evaluated using a single deterministic iteration and the dynamic management strategies were evaluated using 10 stochastic iterations.

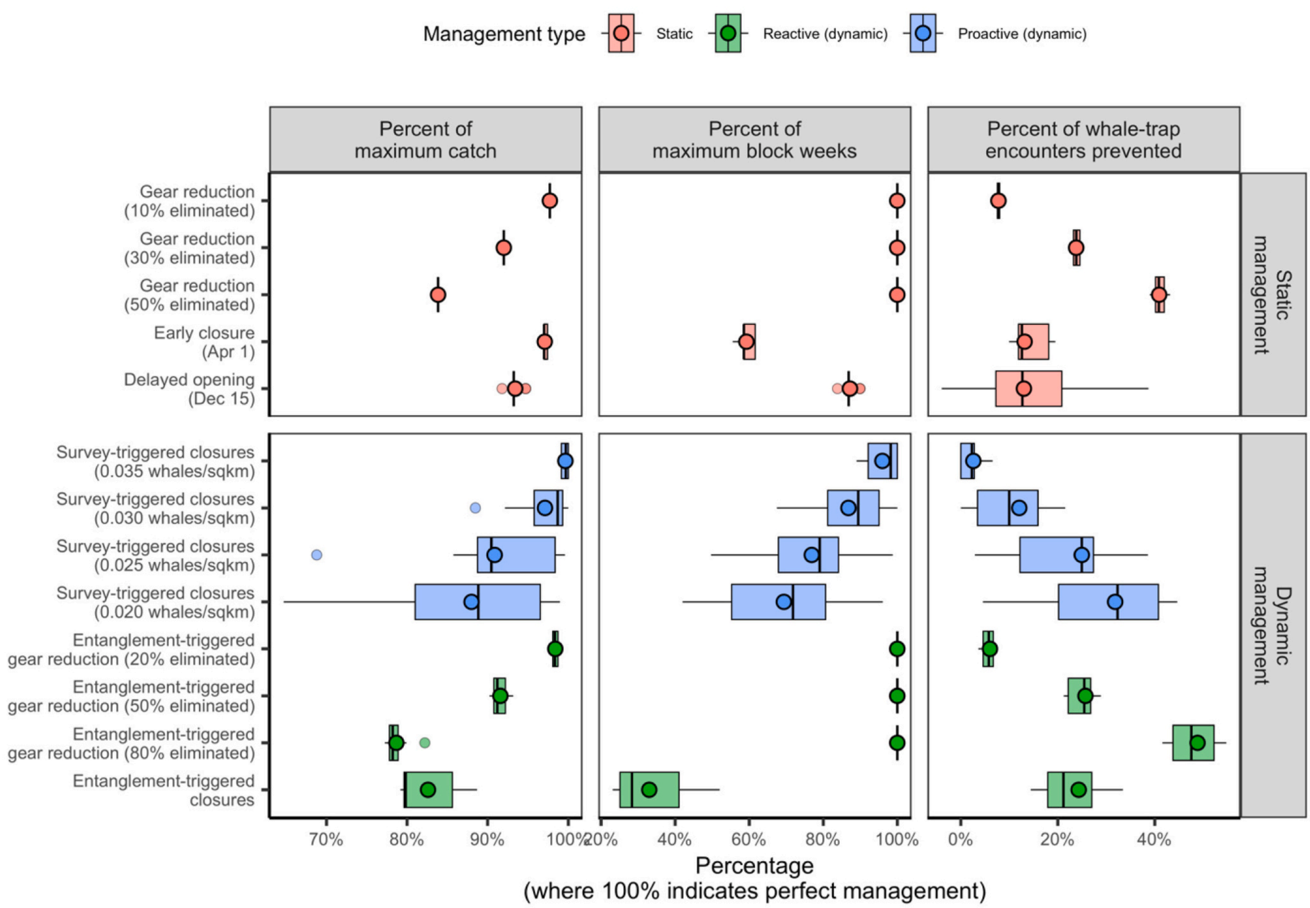

Fig. 2. Tradeoffs among static and dynamic strategies for managing whale entanglement risk over nine commercial fishing seasons (2010–2018). Static management closures are statewide whereas dynamic management closures are zonal. Boxplots indicate the distribution of seasonal performance metrics where the solid line indicates the median, the box indicates the interquartile range (IQR; 25th to 75th percentiles), the whiskers indicate 1.5 times the IQR, and the points beyond the whiskers indicate outliers. Large points indicate summative performance across all nine seasons. For the dynamic management scenarios, seasonal and summative values represent averages of 50 stochastic iterations. The static scenarios were evaluated deterministically. Values of 100 % indicate perfect management for each performance metric.

3. Results

No management strategy performed best across all three performance metrics (Fig. 2; Table S5). If preventing whale entanglements was the only management objective, an 80 % entanglement-triggered gear reduction would be the best management strategy (i.e., it prevents more whale-trap encounters than any other strategy). Furthermore, this strategy maintains an uninterrupted fishing season. However, it results in more lost catch than any other static or dynamic management strategies. Additionally, gear reductions of this magnitude are unprecedented over the evaluated time period (Fig. 3B) and may not be palatable to fishers or managers. If maximizing catch was the primary objective, then a 10 % gear reduction would be the preferred strategy. While the least restrictive survey-triggered closure and entanglement-triggered gear reduction strategies produced marginally higher catches, they resulted in shorter seasons and greater entanglement risk, respectively, and would therefore be less preferable when integrating across performance metrics. If maintaining an uninterrupted fishing season were the primary objective, then the preferred strategy would involve either static or entanglement-triggered gear reductions.

Among the evaluated management strategies, the 30 % gear reduction scenario arguably presents the best balance across the quantitative performance metrics measured (Fig. 2). It maintains an uninterrupted fishing season, maintains high catch, and prevents more entanglement risk than all but the most dramatic (and unprecedented) static and dynamic gear reduction strategies. The relatively high performance of the 30 % gear reduction scenario was consistent or heightened in seasons with delayed openings due to biotoxin contamination or low meat quality (Fig. S21-S25). Fig. 3A illustrates the tradeoff between the catch maximization and risk prevention predicted by our model and could be used to select the gear reduction size that most efficiently meets either management target. In general, the model predicts that increasing gear reductions disproportionately reduce entanglement risk relative to losses in catch (i.e., the gains in entanglement risk prevention are larger than the losses in catch resulting from gear reductions). These predictions are validated by dynamics observed during past fishing seasons (Fig. 3B). For example, during the 2015–16 fishing season, we estimate that approximately 50 % of the usual amount of gear was deployed, yet nearly all of the expected catch was landed (i.e., 87 % of pre-season legal-sized male crabs were landed; Fig. 3B). Although this season saw high revenue losses despite landing the majority of expected catch, this was due more to disruptions in season timing, price dynamics, and fleet behavior more than to the indirect gear reduction (Fisher et al., 2021; Holland and Leonard, 2020). However, it is important to note that gear reductions extend the number of days required to achieve the same level of catch (Fig. 3C).

To reduce entanglement risk more than the 30 % gear reduction scenario, reactive dynamic management triggered by an observed entanglement had to dramatically reduce gear (80 % gear reduction), which significantly reduced seasonal catch and fishing opportunities

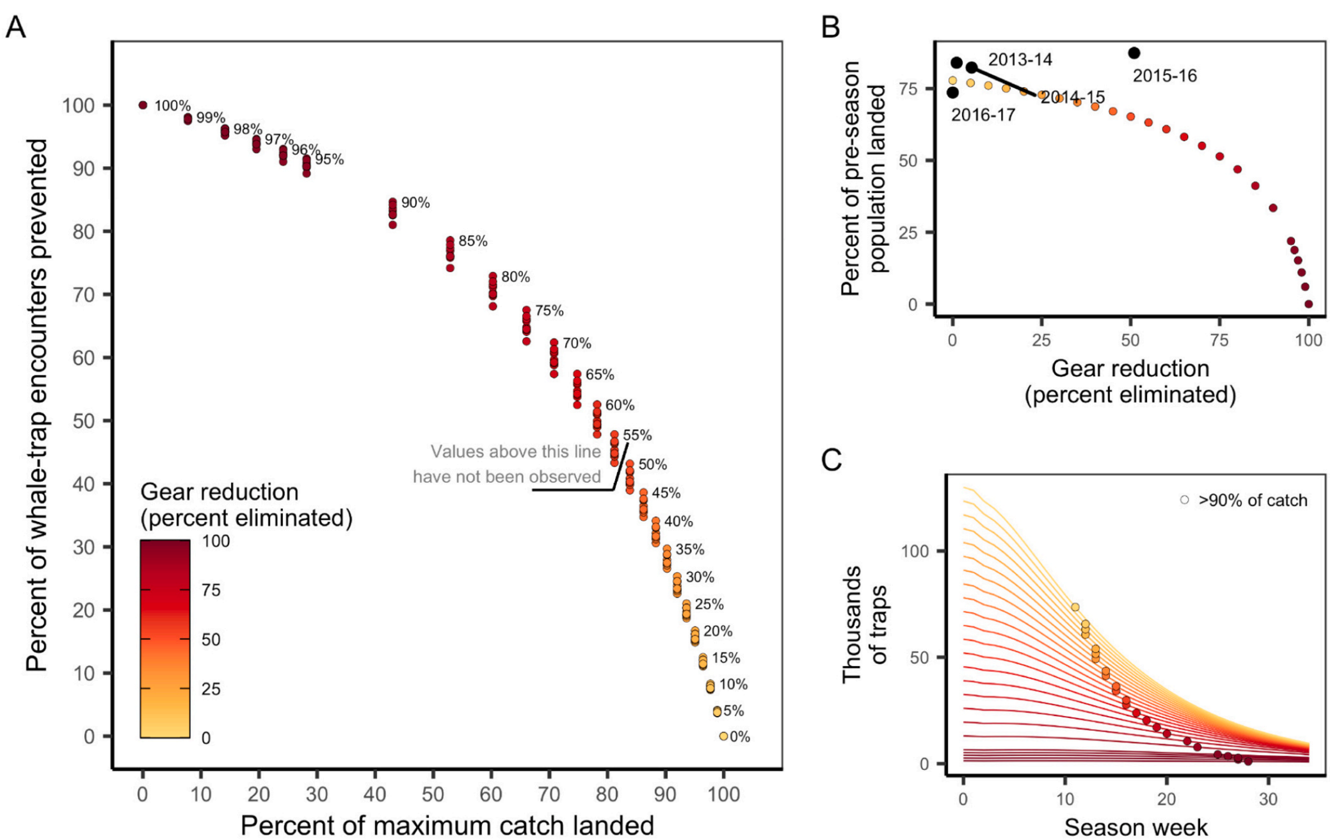

Fig. 3. The (A) performance and (B—C) dynamics of the gear reduction scenarios. In (A), each point represents simulated tradeoffs between catch and entanglement risk in a season. Results differ by season due to differences in the abundance and distribution of whales among seasons (the location and pace of fishing are identical across seasons). In (B), each colored point represents the simulated proportion of the pre-season population captured in each gear reduction scenario (results are identical across seasons). The black points represent the observed relationship between seasonal fishing effort and population depletion estimated for the four Dungeness crab seasons with data. Estimates of population depletion are from Richerson et al. (2020) and estimates of fishing effort are based on the landings receipts data and the "maximum traps rule" (see methods and Fig. S7) and are relative to the season with the largest number of deployed traps (2016–17). In (C), each line represents weekly fishing effort over a season in each gear reduction scenario (results are identical across seasons) and points indicate the week by which >90 % of the season's catch has been landed in each scenario.

(Figs. 2 & S26). Reactive management failed to efficiently reduce entanglement risk because entanglements were rarely observed immediately (0–5 week delay) and management actions in response to an observed entanglement were implemented after a 2-week logistical delay (Fig. S26A); thus, by the time actions were taken (2–7 weeks after the original entanglement), more entanglements had often already occurred (Fig. S26B) and the risk landscape had already shifted (Fig. S27-S29). Gear reductions implemented after long logistical delays were ineffective because effort is already so quickly reduced in this derby fishery (Figs. 3C & S26C). Zonal closures implemented after long delays were ineffective because whales had moved to different zones (Figs. S27-S29).

Proactive dynamic management triggered by observations from whale abundance surveys was even less effective than reactive dynamic management at reducing entanglements, though it was better at preserving fishing opportunities and catch (Fig. 2). Furthermore, the performance of survey-triggered management was highly sensitive to survey design, management zone design, and the choice of the density threshold for triggering management (Figs. 2, S26). We found that the survey design (biweekly fall and monthly spring surveys) and zone design (five large zones) currently being considered for managing whale entanglement risk would result in large-scale closures to the fishery under a range of density thresholds (Figs. 2 & 4). The impacts of zonal closures are not predicted to be geographically equitable, as the fishing grounds of vessels leaving from ports in Zone 3 experienced more closures than all other ports (Fig. 4). Increasing the number of zones (i.e., decreasing the size of closures) would decrease the extent of closures and reduce whale entanglement risk, but the gains are small relative to gear reductions (Figs. S30).

4. Discussion

A perfect management strategy would eliminate the risk of whale entanglements without economic impacts to the commercial fishing fleet. However, tradeoffs between fishing effort and entanglement risk imply that an optimal, though inherently imperfect, management strategy will instead maximize fishing opportunity at a given level of acceptable entanglement risk (Samhouri et al., 2021). Management strategies can also be judged based on their cost effectiveness, enforceability, equity, and robustness to variability or uncertainty. In this case, an optimal strategy would be cheap and enforceable, would avoid disproportionate impacts on any one sector of the fleet (e.g., small vs.

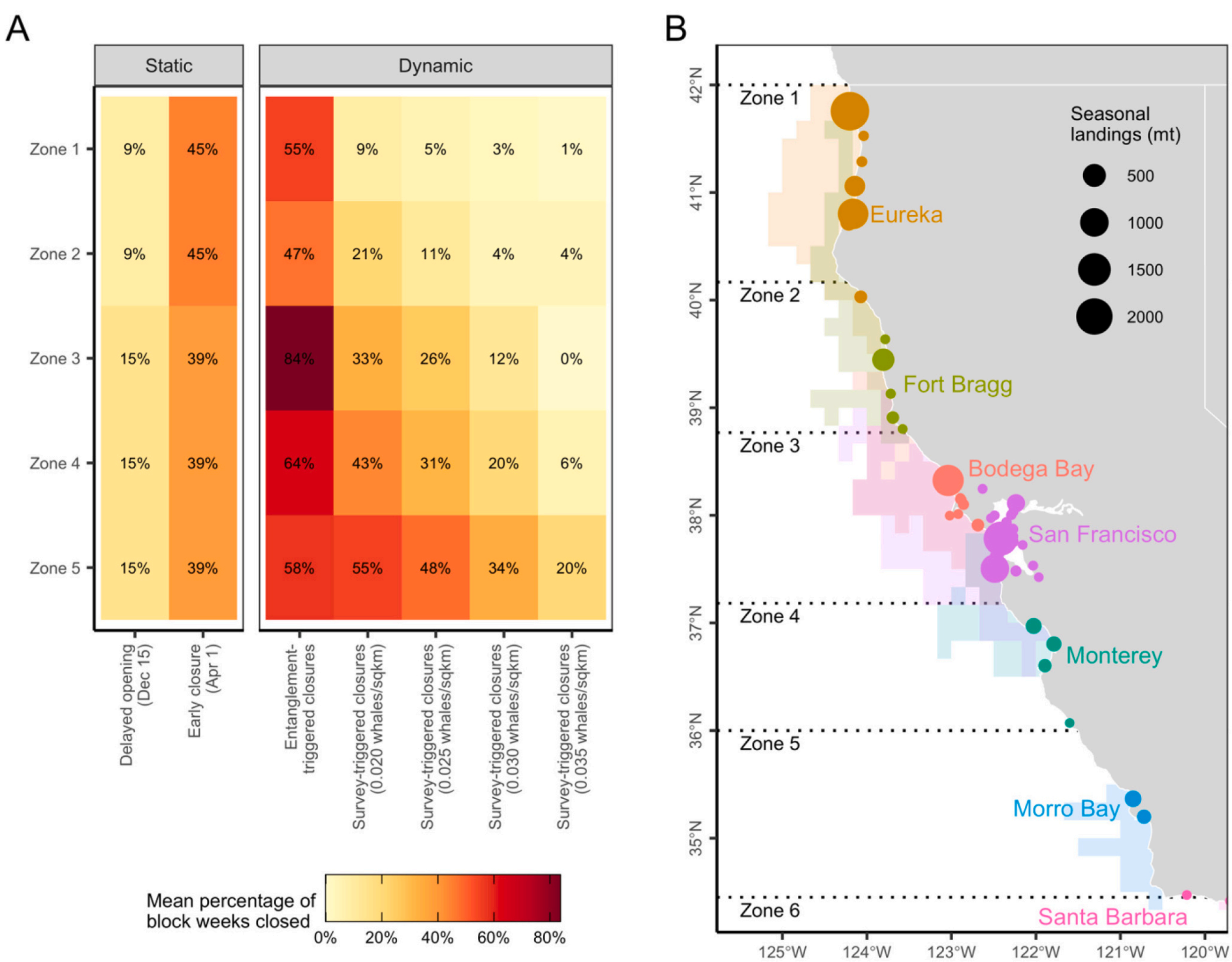

Fig. 4. The (A) simulated extent of closures by risk management zone and management strategy and (B) implied exposure of fishing communities to these closures based on their observed historical fishing grounds. In (A), shading indicates the mean percentage of block weeks closed to fishing across seasons and iterations for each management strategy. The static strategies employ statewide closures while the dynamic strategies employ zonal closures. In (B), points indicate fishing ports and shaded areas indicate the primary fishing grounds used by vessels landing crab in each port complex (labeled). Point size indicates mean seasonal landings from 2010 to 2018. See Fig. S9 for detailed maps of port complex fishing grounds.

large vessels, northern vs. southern home ports; Jardine et al., 2020), and would reliably achieve these objectives across years and with uncertain information on the distribution of whales and/or fishing effort. Although we could not quantitatively evaluate all of these performance criteria, we find that simple static gear reductions outperform complex dynamic management approaches along many of these axes of performance.

Gear reductions avoid uninterrupted seasons, have low predicted impacts on fisheries catch (confirmed by historical observations), and effectively prevent whale entanglement risk by directly reducing the number of vertical lines in the water, among several other benefits. By avoiding closures, gear reductions ensure that fishing is open during the winter holidays when Dungeness crab, a West Coast holiday meal tradition, is in high demand and fetches especially high prices (Mao and Jardine, 2020; Ritzman et al., 2018), and during the spring season, which is critical to smaller vessels that target Dungeness crab over the whole season (Liu et al., 2023). Seary et al. (2022) predict that delayed openings and early closures cost nearly $28 million in ex-vessel revenues across the 2019–20 and 2020–21 California fishing seasons; gear reductions would eliminate the contribution of entanglement-related closures to such losses. Furthermore, gear reductions were robust to delayed openings resulting from biotoxin contamination or low meat quality, while early closures triggered by either static or dynamic management severely compressed fishing opportunities in years with delayed openings. Unlike proactive dynamic management, which requires financial investment in whale surveys and a panel of experts to regularly interpret the results of these surveys (CDFW, 2020), gear reductions add no new management costs or complexity. Unlike strategies employing zonal closures, gear reductions introduce no biases in the geographical equity of entanglement risk management.

However, gear reductions will require careful deliberation and stakeholder engagement to ensure equity and fairness. For example, gear reductions could threaten economic viability for smaller vessels with lower gear allotments, as these vessels are already the most vulnerable to season delays and closures due to lower mobility and higher specialization (Fisher et al., 2021; Jardine et al., 2020; Liu et al., 2023). Furthermore, gear reductions could compromise economic viability for all vessels by extending the number of days required to achieve the same level of catch. A longer crab season duration not only increases the costs associated with crab fishing but occupies time that could otherwise be spent participating in non-crab fisheries (Fisher et al., 2021; Liu et al., 2023). For example, Holland and Leonard (2020) estimate that revenue losses from reduced effort in non-crab fisheries during the 2015–16 disaster season were comparable to those from the crab fishery, highlighting the importance of being able to participate in multiple fisheries to many fishers (Fisher et al., 2021; Liu et al., 2023). Finally, gear reductions may lower the resale value of crab permits, which are transferable and currently have asking prices of US $42,000–320,000 (Table S2) (Dock Street Brokers, 2023). These limitations demand consideration as managers choose between alternative strategies.

The ability for gear reductions to reduce entanglement risk with minimal impacts on fishing opportunities has been reported in many other trap fisheries. Riekkola et al. (2023) found that mandatory summer gear reductions in the Washington Dungeness crab fishery reduced blue whale (*Balaenoptera musculus*) and humpback whale entanglement risk by up to 20 % and 78 %, respectively, without a substantial negative impact to fleet-wide revenue, landings, and catch-per-unit-efforts. Myers and Moore (2020) found that gear reductions in the Maine lobster (*Homarus americanus*) fishery would result in fewer right whale (*Eubalaena glacialis*) entanglements and equal, if not higher, fishery revenues. Relatedly, gear modifications that reduced the amount of line per trap lowered humpback whale entanglements in the Western Australia rock lobster (*Panulirus cygnus*) fishery by >25 %, without substantial economic impacts to the fishery (How et al., 2021). These studies collectively illustrate the promise for simple management approaches to balance complex fisheries and conservation tradeoffs.

Ultimately, the entanglement of endangered species in fixed-gear fisheries poses a unique challenge to dynamic ocean management. In contrast to fisheries that use mobile gear (e.g., trawls, seines), fisheries that use fixed gear, which is set, soaked, and retrieved later (e.g., traps, gillnets, longlines), cannot as quickly and cost-effectively relocate gear in response to bycatch risk. This is especially true for trap fisheries, which rely on long soak times (1–4 days) that can become even more extended during periods of unfavorable weather. This means that the risk landscape has shifted by the time actions are taken to relocate fishing effort. In the worst case scenario, this can lead to fishing effort getting concentrated in areas of even higher whale densities. Furthermore, traps are left to soak unattended, which hinders rapid entanglement response times, unlike in mobile-gear fisheries or in fixed-gear fisheries in which soak times are short and gear is monitored. As a result, most confirmed entanglements are observed on large delays, further undermining the relevance and effectiveness of reactive management triggered by entanglements. The bycatch of endangered species further magnifies challenges for dynamic ocean management as the entanglement of even a few individuals can threaten population health or risk widespread fishery closures. In California, for example, three confirmed humpback whale entanglements in commercial Dungeness crab fishing gear would trigger the statewide closure of the fishery (CDFW, 2020). As a result, entanglement-triggered management could disincentivize fishers from reporting entanglements (e.g., >21 % of confirmed whale entanglements in 2016 were reported by fishers; Saez et al., 2020), which could reduce whale entanglement response rates and increase injury and mortality from entanglements.

Although the dynamic management strategies performed no better than simpler static management strategies, there may be opportunities for new dynamic management approaches to generate better outcomes. First, due to the coarse spatial resolution of our fleet dynamics model (18 × 18 km fishing blocks), we were unable to evaluate fine-scale spatial closures such as depth-based closures, which are identified as a potential management response in the current management plan (CDFW, 2021; CDFW, 2020) and were used for the first time in the 2022–23 season. Although Samhouri et al. (2021) found that closing fishing grounds inside 30 fathoms would have exacerbated entanglement risk during the 2014–16 marine heatwave, exploration of alternative depth-based management triggers and actions could yield more promising results. Second, we did not evaluate the potential for near real-time forecasts of whale distributions (e.g., as operationalized for West Coast blue whales; Hazen et al., 2018) to guide either dynamic mandated closures or voluntary avoidance of whale hotspots. Although simulation exercises suggest that such strategies are theoretically effective (Dunn et al., 2016), their real-world efficacy will depend on the accuracy of the forecast, behavior of fishers in response to forecasts, ability of fishers to respond to forecasts in a timely manner, and the regulatory appetite for implementing and enforcing complex regulations or for relying on voluntary actions.

More regular whale abundance surveys and smaller management zones may represent a more viable and effective dynamic management strategy, but would also increase management complexity and expense. Furthermore, surveys depend on favorable weather conditions, which can limit timeliness. If proactive risk management based on whale abundance surveys is to remain a tool in this fishery, it will be more effective with fiscal support for systematic surveys with abundance thresholds pegged to the survey design. Currently, surveys are ad-hoc, insecurely funded, and appear to be interpreted based on the number of whales observed in the survey rather than on the number of whales that the survey extrapolates to the management zone (CDCFGWG, 2020). The latter is illogical because survey designs are inconsistent: despite identical whale abundances, a survey with greater coverage or detectability will observe more whales, on average, than a survey with lower coverage or detectability. To avoid arbitrary management decisions, managers should consider adopting a standardized survey design and/or by density-based thresholds that are less sensitive to survey design. Management strategy evaluations, such as the one presented here, provide a useful tool for evaluating the performance of potential survey designs, density thresholds, and management zone arrangements (Smith et al., 2021) and for anticipating whether the benefits of increased complexity outweigh the costs (e.g., Mangin et al., 2018).

To be successful, future scientific research and management decisions should consider the distributional impacts and equity of alternative bycatch avoidance strategies. The Dungeness crab fishing fleet comprises many vessel sizes, permit tiers, portfolio strategies, and home ports; preferred management strategies that avoid or minimize disproportionate impacts on any one sector of the fleet are likely to be better received than those that favor some sectors over others. Lessons from historical closures and predictions from our simulation model can partially inform these considerations. Fisher et al. (2021) found that northern region fishing communities were more disrupted by the 2015–16 closures than central region fishing communities due to their comparably higher reliance and specialization on Dungeness crab. Jardine et al. (2020) and Fisher et al. (2021) both found that smaller vessels (<40 ft) were more impacted by closures than larger vessels due to their lower profit margins and mobility. Although our model does not simulate vessel-level dynamics and therefore cannot capture vessel-level impacts of alternative management strategies, it suggests that zones 3, 4, and 5, which correspond to the fishing grounds of Bodega Bay/San Francisco, Monterey, and Morro Bay, would receive the most extensive closures based on current regulations (Fig. 4). Key expansions in future modeling efforts may include (i) collaborating with stakeholders to identify performance metrics that capture the equity of alternative strategies and (ii) leveraging agent-based modeling approaches (Burgess et al., 2020) to understand the impacts of management on subsets of the Dungeness crab fleet.

Fishery resources are nested within complex social-ecological systems and support diverse stakeholders with varied, and sometimes competing, values and objectives. Climate change is disrupting these complex social-ecological systems through well-documented challenges such as shifting distributions, productivity, phenology, and life history (IPCC, 2019) and through emerging challenges such as increasing harmful algal blooms and marine heatwaves (Santora et al., 2020) that are now commonly triggering federally-declared fishery disasters (Bellquist et al., 2021). In many cases, these complex challenges will require complex solutions (Lewison et al., 2015), fueled by rapidly growing data availability and analysis capacity (Leape et al., 2020). However, simple solutions may sometimes most cheaply and effectively address conservation challenges with complex tradeoffs. Furthermore, simple solutions can be effective placeholders while more complex measures are developed and proven effective (Wiedenmann et al., 2019). However, there are no "silver bullet" solutions to complex social-ecological problems and management strategy evaluation presents the opportunity to weigh the costs and benefits of alternative approaches (Punt et al., 2016), simple or complex.

CRediT authorship contribution statement

Christopher M. Free: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Lyall F. Bellquist:** Writing – review & editing. **Karin A. Forney:** Data curation, Writing – review & editing. **Jenn Humberstone:** Writing – review & editing. **Kate Kauer:** Writing – review & editing. **Qi Lee:** Writing – review & editing. **Owen R. Liu:** Writing – review & editing. **Jameal F. Samhouri:** Writing – review & editing. **Jono R. Wilson:** Writing – review & editing. **Darcy Bradley:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Christopher Free reports financial support was provided by The Nature Conservancy.

Data availability

All data and code are available on GitHub here: https://github.com/cfree14/dungeness

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110249.

References

Armstrong, D.A., McDonald, P.S., Kruse, G.H., Hines, A.H., Orensanz, J.M., 2011. A crab for all seasons: The confluence of fisheries and climate as drivers of crab abundance and distribution. In: Biology and Management of Exploited Crab Populations under Climate Change. Presented at the Biology and Management of Exploited Crab Populations under Climate Change. Alaska Sea Grant, University of Alaska Fairbanks, pp. 1–47. https://doi.org/10.4027/bmecpcc.2010.05.

Becker, E.A., Forney, K.A., Fiedler, P.C., Barlow, J., Chivers, S.J., Edwards, C.A., Moore, A.M., Redfern, J.V., 2016. Moving towards Dynamic Ocean management: How well do Modeled Ocean products predict species distributions? Remote Sens. 8, 149. https://doi.org/10.3390/rs8020149.

Becker, E.A., Forney, K.A., Redfern, J.V., Barlow, J., Jacox, M.G., Roberts, J.J., Palacios, D.M., 2019. Predicting cetacean abundance and distribution in a changing climate. Divers. Distrib. 25, 626–643. https://doi.org/10.1111/ddi.12867.

Bellquist, L., Saccomanno, V., Semmens, B.X., Gleason, M., Wilson, J., 2021. The rise in climate change-induced federal fishery disasters in the United States. PeerJ 9, e11186. https://doi.org/10.7717/peerj.11186.

Bond, N.A., Cronin, M.F., Freeland, H., Mantua, N., 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophys. Res. Lett. 42, 3414–3420. https://doi.org/10.1002/2015GL063306.

Brandon, J.R., Punt, A.E., Moreno, P., Reeves, R.R., 2017. Toward a tier system approach for calculating limits on human-caused mortality of marine mammals. ICES J. Mar. Sci. 74, 877–887. https://doi.org/10.1093/icesjms/fsw202.

Bunnefeld, N., Hoshino, E., Milner-Gulland, E.J., 2011. Management strategy evaluation: a powerful tool for conservation? Trends Ecol. Evol. 26, 441–447. https://doi.org/10.1016/j.tree.2011.05.003.

Burgess, M.G., Carrella, E., Drexler, M., Axtell, R.L., Bailey, R.M., Watson, J.R., Cabral, R.B., Clemence, M., Costello, C., Dorsett, C., Gaines, S.D., Klein, E.S., Koralus, P., Leonard, G., Levin, S.A., Little, L.R., Lynham, J., Madsen, J.K., Merkl, A., Owashi, B., Saul, S.E., Putten, I.E. van, Wilcox, S., 2020. Opportunities for agent-based modelling in human dimensions of fisheries. Fish Fish. 21, 570–587. doi:https://doi.org/10.1111/faf.12447.

Calambokidis, J., Barlow, J., 2020. Updated abundance estimates for blue and humpback whales along the U.S. west coast using data through 2018 20.

CDCFGWG, 2017. Draft Risk Assessment and Mitigation Program (RAMP): Voluntary Pilot, 2017–18 CA Dungeness Crab Fishing Season.

CDCFGWG, 2020. 2019–20 RAMP. Working Group Reflections, California Dungeness Crab Fishing Gear Working Group.

CDCFGWG, 2020a. 2019–20 Risk Assessments: Available Data. California Dungeness Crab Fishing Gear Working Group.

CDFW, 2020. Risk Assessment Mitigation Program: Commercial Dungeness Crab Fishery. California Code of Regulations, Title, p. 14.
CDFW, 2021. Draft Conservation Plan for California's Commercial Dungeness Crab Fishery.
Clapham, P.J., Mead, J.G., 1999. *Megaptera novaeangliae*. Mamm. Species 604, 1–9. https://doi.org/10.2307/3504352.
Dock Street Brokers, 2023. Permits - West Coast Permits [WWW Document]. Dock Str. Brok. URL https://dockstreetbrokers.com/permits/west-coast-permits (accessed 8.8.23).
Dunn, D.C., Boustany, A.M., Halpin, P.N., 2011. Spatio-temporal management of fisheries to reduce by-catch and increase fishing selectivity. Fish Fish. 12, 110–119. https://doi.org/10.1111/j.1467-2979.2010.00388.x.
Dunn, D.C., Maxwell, S.M., Boustany, A.M., Halpin, P.N., 2016. Dynamic Ocean management increases the efficiency and efficacy of fisheries management. Proc. Natl. Acad. Sci. 113, 668–673. https://doi.org/10.1073/pnas.1513626113.
Feist, B.E., Samhouri, J.F., Forney, K.A., Saez, L.E., 2021. Footprints of fixed-gear fisheries in relation to rising whale entanglements on the U.S. West Coast. Fish. Manag. Ecol. 28, 283–294. https://doi.org/10.1111/fme.12478.
Fisher, M.C., Moore, S.K., Jardine, S.L., Watson, J.R., Samhouri, J.F., 2021. Climate shock effects and mediation in fisheries. Proc. Natl. Acad. Sci. 118 https://doi.org/10.1073/pnas.2014379117.
Free, C.M., Vargas Poulsen, C., Bellquist, L.F., Wassermann, S.N., Oken, K.L., 2022. The CALFISH database: a century of California's non-confidential fisheries landings and participation data. Ecol. Inform. 69, 101599 https://doi.org/10.1016/j.ecoinf.2022.101599.
Hazen, E.L., Scales, K.L., Maxwell, S.M., Briscoe, D.K., Welch, H., Bograd, S.J., Bailey, H., Benson, S.R., Eguchi, T., Dewar, H., Kohin, S., Costa, D.P., Crowder, L.B., Lewison, R. L., 2018. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. Sci. Adv. 4, eaar 3001. https://doi.org/10.1126/sciadv.aar3001.
Hilborn, R., Walters, C.J., 1992. Quantitative Fisheries Stock Assessment: Choice. Dynamics and Uncertainty. Chapman & Hall, London.
Holland, D.S., Leonard, J., 2020. Is a delay a disaster? Economic impacts of the delay of the California Dungeness crab fishery due to a harmful algal bloom. Harmful Algae 98, 101904. https://doi.org/10.1016/j.hal.2020.101904.
How, J.R., de la Mare, W.K., Coughran, D.K., Double, M.C., de Lestang, S., 2021. Gear modifications reduced humpback whale entanglements in a commercial rock lobster fishery. Mar. Mammal Sci. n/a. https://doi.org/10.1111/mms.12774.
Howell, E.A., Kobayashi, D.R., Parker, D.M., Balazs, G.H., Polovina, J.J., 2008. TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles Caretta caretta in the Hawaii-based pelagic longline fishery. Endanger. Species Res. 5, 267–278. https://doi.org/10.3354/esr00096.
IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.
Jardine, S.L., Fisher, M.C., Moore, S.K., Samhouri, J.F., 2020. Inequality in the economic impacts from climate shocks in fisheries: the case of harmful algal blooms. Ecol. Econ. 176, 106691 https://doi.org/10.1016/j.ecolecon.2020.106691.
Knowlton, A.R., Robbins, J., Landry, S., McKenna, H.A., Kraus, S.D., Werner, T.B., 2016. Effects of fishing rope strength on the severity of large whale entanglements. Conserv. Biol. 30, 318–328. https://doi.org/10.1111/cobi.12590.
Lagerquist, B.A., Mate, B.R., Ortega-Ortiz, J.G., Winsor, M., Urbán-Ramirez, J., 2008. Migratory movements and surfacing rates of humpback whales (*Megaptera novaeangliae*) satellite tagged at Socorro Island, Mexico. Mar. Mammal Sci. 24, 815–830. https://doi.org/10.1111/j.1748-7692.2008.00217.x.
Leape, J., Abbott, M., Sakaguchi, H., Brett, A., Cao, L., Chand, K., Golbuu, Y., Martin, T., Myksvoll, M.S., 2020. Technology. Data and New Models for Sustainably Managing Ocean Resources, World Resources Institute, Washington, DC.
Lewison, R., Hobday, A.J., Maxwell, S., Hazen, E., Hartog, J.R., Dunn, D.C., Briscoe, D., Fossette, S., O'Keefe, C.E., Barnes, M., Abecassis, M., Bograd, S., Bethoney, N.D., Bailey, H., Wiley, D., Andrews, S., Hazen, L., Crowder, L.B., 2015. Dynamic Ocean management: identifying the critical ingredients of dynamic approaches to ocean resource management. BioScience 65, 486–498. https://doi.org/10.1093/biosci/biv018.
Lewison, R.L., Crowder, L.B., Wallace, B.P., Moore, J.E., Cox, T., Zydelis, R., McDonald, S., DiMatteo, A., Dunn, D.C., Kot, C.Y., Bjorkland, R., Kelez, S., Soykan, C., Stewart, K.R., Sims, M., Boustany, A., Read, A.J., Halpin, P., Nichols, W. J., Safina, C., 2014. Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. Proc. Natl. Acad. Sci. 111, 5271–5276. https://doi.org/10.1073/pnas.1318960111.
Liu, O.R., Fisher, M., Feist, B.E., Abrahms, B., Richerson, K., Samhouri, J.F., 2023. Mobility and flexibility enable resilience of human harvesters to environmental perturbation. Glob. Environ. Change 78, 102629. https://doi.org/10.1016/j.gloenvcha.2022.102629.
Mangin, T., Costello, C., Anderson, J., Arnason, R., Elliott, M., Gaines, S.D., Hilborn, R., Peterson, E., Sumaila, R., 2018. Are fishery management upgrades worth the cost? PLoS One 13, e0204258-24. https://doi.org/10.1371/journal.pone.0204258.
Mao, J., Jardine, S.L., 2020. Market impacts of a toxic algae event: the case of California Dungeness crab. Mar. Resour. Econ. 35, 1–20. https://doi.org/10.1086/707643.
Mate, B.R., Gisiner, R., Mobley, J., 1998. Local and migratory movements of Hawaiian humpback whales tracked by satellite telemetry. Can. J. Zool. 76, 863–868. https://doi.org/10.1139/z98-008.
Maxwell, S.M., Hazen, E.L., Lewison, R.L., Dunn, D.C., Bailey, H., Bograd, S.J., Briscoe, D.K., Fossette, S., Hobday, A.J., Bennett, M., Benson, S., Caldwell, M.R., Costa, D.P., Dewar, H., Eguchi, T., Hazen, L., Kohin, S., Sippel, T., Crowder, L.B., 2015. Dynamic Ocean management: defining and conceptualizing real-time management of the ocean. Mar. Policy 58, 42–50. https://doi.org/10.1016/j.marpol.2015.03.014.
McCabe, R.M., Hickey, B.M., Kudela, R.M., Lefebvre, K.A., Adams, N.G., Bill, B.D., Gulland, F.M.D., Thomson, R.E., Cochlan, W.P., Trainer, V.L., 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. Geophys. Res. Lett. 43, 10,366–10,376. https://doi.org/10.1002/2016GL070023.
McKibben, S.M., Peterson, W., Wood, A.M., Trainer, V.L., Hunter, M., White, A.E., 2017. Climatic regulation of the neurotoxin domoic acid. Proc. Natl. Acad. Sci. 114, 239–244. https://doi.org/10.1073/pnas.1606798114.
Myers, H.J., Moore, M.J., 2020. Reducing effort in the U.S. American lobster (Homarus americanus) fishery to prevent North Atlantic right whale (Eubalaena glacialis) entanglements may support higher profits and long-term sustainability. Mar. Policy 118, 104017. https://doi.org/10.1016/j.marpol.2020.104017.
O'Keefe, C.E., Cadrin, S.X., Stokesbury, K.D.E., 2014. Evaluating effectiveness of time/area closures, quotas/caps, and fleet communications to reduce fisheries bycatch. ICES J. Mar. Sci. 71, 1286–1297. https://doi.org/10.1093/icesjms/fst063.
Pace III, R.M., Williams, R., Kraus, S.D., Knowlton, A.R., Pettis, H.M., 2021. Cryptic mortality of North Atlantic right whales. Conserv. Sci. Pract. 3, e346 https://doi.org/10.1111/csp2.346.
Punt, A.E., Butterworth, D.S., Oliveira, J.A.A.D., Haddon, M., 2016. Management strategy evaluation: best practices. Fish Fish. 17, 303–334. https://doi.org/10.1111/faf.12104.
Punt, A.E., Moreno, P., Brandon, J.R., Mathews, M.A., 2018. Conserving and recovering vulnerable marine species: a comprehensive evaluation of the US approach for marine mammals. ICES J. Mar. Sci. 75, 1813–1831. https://doi.org/10.1093/icesjms/fsy049.
Punt, A.E., Siple, M., Sigurðsson, G.M., Víkingsson, G., Francis, T.B., Granquist, S.M., Hammond, P.S., Heinemann, D., Long, K.J., Moore, J.E., Sepúlveda, M., Reeves, R.R., Wade, P.R., Williams, R., Zerbini, A.N., 2020. Evaluating management strategies for marine mammal populations: an example for multiple species and multiple fishing sectors in Iceland. Can. J. Fish. Aquat. Sci. 77, 1316–1331. https://doi.org/10.1139/cjfas-2019-0386.
Rasmuson, L.K., 2013. The biology, ecology and fishery of the Dungeness crab, Cancer magister. In: Lesser, M. (Ed.), Advances in Marine Biology. Academic Press, pp. 95–148. https://doi.org/10.1016/B978-0-12-410498-3.00003-3.
Richerson, K., Punt, A.E., Holland, D.S., 2020. Nearly a half century of high but sustainable exploitation in the Dungeness crab (Cancer magister) fishery. Fish. Res. 226, 105528 https://doi.org/10.1016/j.fishres.2020.105528.
Riekkola, L., Liu, O.R., Feist, B.E., Forney, K.A., Abrahms, B., Hazen, E.L., Samhouri, J.F., 2023. Retrospective analysis of measures to reduce large whale entanglements in a lucrative commercial fishery. Biol. Conserv. 278, 109880 https://doi.org/10.1016/j.biocon.2022.109880.
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 U.S. west coast harmful algal bloom. Harmful Algae 80, 35–45. https://doi.org/10.1016/j.hal.2018.09.002.
Rockwood, R.C., Calambokidis, J., Jahncke, J., 2017. High mortality of blue, humpback and fin whales from modeling of vessel collisions on the U.S. west coast suggests population impacts and insufficient protection. PLoS One 12, e0183052. https://doi.org/10.1371/journal.pone.0183052.
Rowcliffe, J.M., Cowlishaw, G., Long, J., 2003. A model of human hunting impacts in multi-prey communities: modelling hunting in multi-prey communities. J. Appl. Ecol. 40, 872–889. https://doi.org/10.1046/j.1365-2664.2003.00841.x.
Saez, L.E., Lawson, D., DeAngelis, M., 2020. Large Whale Entanglements off the U.S. West Coast, from 1982-2017 (No. NMFS-OPR-63). NOAA Technical Memorandum. National Marine Fisheries Service.
Samhouri, J.F., Feist, B.E., Fisher, M.C., Liu, O., Woodman, S.M., Abrahms, B., Forney, K. A., Hazen, E.L., Lawson, D., Redfern, J., Saez, L.E., 2021. Marine heatwave challenges solutions to human–wildlife conflict. Proc. R. Soc. B Biol. Sci. 288, 20211607. https://doi.org/10.1098/rspb.2021.1607.
Santora, J.A., Mantua, N.J., Schroeder, I.D., Field, J.C., Hazen, E.L., Bograd, S.J., Sydeman, W.J., Wells, B.K., Calambokidis, J., Saez, L., Lawson, D., Forney, K.A., 2020. Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. Nat. Commun. 11, 536. https://doi.org/10.1038/s41467-019-14215-w.
Seary, R., Santora, J.A., Tommasi, D., Thompson, A., Bograd, S.J., Richerson, K., Brodie, S., Holland, D., 2022. Revenue loss due to whale entanglement mitigation and fishery closures. Sci. Rep. 12, 21554. https://doi.org/10.1038/s41598-022-24867-2.
Smith, J.A., Tommasi, D., Welch, H., Hazen, E.L., Sweeney, J., Brodie, S., Muhling, B., Stohs, S.M., Jacox, M.G., 2021. Comparing dynamic and static time-area closures for bycatch mitigation: a management strategy evaluation of a swordfish fishery. Front. Mar. Sci. 8, 630607 https://doi.org/10.3389/fmars.2021.630607.
Vasconcellos, M., Cochrane, K., 2005. Overview of world status of data-limited fisheries: Inferences from landings statistics. In: Kruse, G.H., Gallucci, V.F., Hay, D.E., Perry, R. I., Peterman, R.M., Shirley, T.C., Spencer, P.D., Wilson, B., Woodby, D. (Eds.), Fisheries Assessment and Management in Data-Limited Situations. Alaska Sea Grant College Program.
Wiedenmann, J., Free, C.M., Jensen, O.P., 2019. Evaluating the performance of data-limited methods for setting catch targets through application to data-rich stocks: A case study using northeast U.S. fish stocks. Fish. Res. 209, 129–142. https://doi.org/10.1016/j.fishres.2018.09.018.