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Dynamic strategies offer potential to reduce lethal ship collisions with large whales under changing climate conditions

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ABSTRACT

Dynamic ocean management (DOM), a type of marine spatial planning in which management decisions are updated in response to changing environmental, biological, or socioeconomic conditions, holds promise for balancing tradeoffs between conservation and marine resource use. However, as climate change continues to drive unprecedented oceanic changes, it is critical to evaluate how such tradeoffs may vary under different environmental regimes to ensure management strategies remain robust. To address this need, we explored blue whale ship strike management scenarios in the Southern California Bight, USA, an area that currently uses voluntary vessel speed reductions to mitigate risk of lethal ship collisions. We compared two simulated DOM strategies – a '*daily strategy*' that implemented speed reductions in response to whale habitat conditions on a daily basis, and a '*seasonal strategy*' that implemented speed reductions in response to whale habitat conditions on a seasonal basis – with a '*fixed strategy*' that implemented speed reductions for a fixed time period each year, irrespective of environmental conditions. We evaluated the capacity of these strategies to balance tradeoffs between whale conservation and shipping activities over a 17-year study period. Critically, we assessed these tradeoffs before, during, and after a record marine heatwave to evaluate the relative utilities of these strategies during anomalous ocean conditions. Over the 17-year study period, seasonal and daily DOM strategies achieved a 6.4–10.7% improvement in expected whale protection from lethal collision, respectively, without the need for additional vessel speed reductions, as compared to the fixed strategy. The benefit of DOM strategies has grown in the last decade and was accentuated during and after the marine heatwave event, with the daily DOM strategy seeing a 16.2% increase in whale protection compared to the fixed strategy in the five years prior to the event, versus a 26.5% increase in the five years during and after the event. Such results indicate that dynamic ocean management is a valuable strategy for coping with anomalous environmental conditions, which will become increasingly important as the climate continues to change. Moreover, our study emphasizes the importance of assessing tradeoffs between conservation goals and human activities over a range of environmental conditions in order to evaluate the robustness of management strategies to climate change.

1. Introduction

Supporting biodiversity conservation in tandem with marine resource use remains a key challenge for ocean management. Marine spatial planning, in which areas of the ocean are zoned for different human uses, has become a valuable management strategy for balancing tradeoffs between conservation goals and human activities [1,2]. For example, marine protected areas are a prevalent form of marine spatial planning that are implemented globally [1]. However, there is increasing appreciation that marine habitats tend to be highly dynamic and will likely become more so under increasing climate variability and change, challenging traditional management approaches [3–6]. Static

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management strategies may not adequately account for changing environments, species distributions, or human activities, and, importantly, are inflexible to anomalous events such as marine heatwaves [7,8]. As a result, dynamic ocean management (DOM), whereby management decisions are updated in response to changing environmental, biological, or socioeconomic conditions, has gained traction as a strategy for addressing this problem [9–11].

Despite increasing interest in DOM, its implementation has been limited [12]. Although DOM has been proposed as a climate-ready strategy for ecosystem-based management, evaluation of its efficacy has been limited outside of the fisheries sector [12] (but see [13]). In addition, stakeholders may desire evidence that new management strategies will generate improvements, and that these improvements can be sustained across a range of ocean conditions. The provision of evidence for tradeoffs between conservation goals and human activities led to significant advancements in earlier literature around marine spatial planning [14], allowing user groups to visualize the nature of tradeoffs in relation to potential management strategies. However, few studies have quantified the dynamic nature of such tradeoffs, and whether and how they shift under different environmental conditions. This gap in knowledge is particularly concerning with increased appreciation of human-induced rapid environmental change [15], leaving open the question of how tradeoffs associated with DOM are affected by climate variability and change.

Here we evaluate the potential of dynamic management to balance tradeoffs between conservation goals and human activities under varying environmental conditions, using a case study on lethal ship collisions with blue whales. Ship strikes have been identified as one of the main factors hindering the recovery of large whales, representing a significant conflict with global shipping activities [16–21]. The years of 2018 and 2019 saw the highest number of lethal ship strikes to whales on record in the western USA (NOAA National Stranding Database, https://mmhsrp.nmfs.noaa.gov/mmhsrp/), and global shipping traffic is projected to increase up to 12-fold in coming decades [22]. Most ship strikes occur in areas with a high spatial overlap between heavy ship traffic, typically coastal shipping lanes into ports, and whale feeding habitat that see prolonged periods of whale occurrence [17,23]. Of the large whales that migrate along the U.S. west coast, blue whales (*Balaenoptera musculus*), a globally Endangered species, are considered the most threatened by ship strike [17]. The Southern California Bight, USA (32.5–34.5°N, 117–120°W; hereafter, SCB), has been consistently identified as a hotspot for ship strikes to blue whales [17,24]. Annually, this highly trafficked area sees almost $300 billion dollars of ship-born cargo travel through shipping lanes (termed the Traffic Separation Scheme; TSS) to the ports of Los Angeles and Long Beach (Fig. 1). The SCB is also a foraging hot spot for blue whales during their migration [25,26], leading to high spatial overlap between shipping vessels and blue whales. In addition, blue whales migrated into the SCB earlier during a record marine heatwave that occurred in 2014–2016 [27,28], highlighting the important role that ocean conditions may play in shifting the timing of elevated ship strike risk between years.

Most ship strike mitigation efforts fall along a spectrum of relying on long-term patterns in whale occurrence versus using immediate information on whale presence. For instance, vessel speed reduction rules for reducing strikes to North Atlantic right along the U.S. east coast are based on historic detections as well as whale aggregations observed in real-time that inform dynamic management areas [13,29,30]. Additionally, acoustic gliders and a series of acoustic recording buoys along the Boston shipping channels provide near real-time information on when whales are present to inform potential vessel speed rules [31,32]. Similar holistic efforts have recently been launched on the west coast to incorporate blue whale detections and habitat conditions into ship strike management in the SCB (*see* www.whalesafe.com). Currently, the National Oceanic and Atmospheric Administration seeks to mitigate risk of lethal ship collisions in the SCB by requesting a voluntary vessel speed reduction to 10 knots in the TSS during blues whales' peak foraging season in summer and early fall [17,27,33]. A vessel speed restriction of 10 knots was shown to significantly reduce the expected chance of lethal collisions with North Atlantic right whales (*Eubalaena glacialis*) along the eastern seaboard [34], and although there is debate about whether this speed limit is sufficient [35,36], it has been adopted into west coast ship strike management because no comparable data are available for other whale species.

In this study, we compared two dynamic ocean management strategies – a '*daily strategy*' that implements speed reductions in response to whale habitat conditions on a daily basis, and a '*seasonal strategy*' that implements reductions in response to whale habitat conditions on a seasonal basis – with a '*fixed strategy*' that implements speed reductions for a fixed time period each year, irrespective of environmental conditions. We evaluated the capacity of these strategies to balance tradeoffs between whale conservation and shipping activities. We further assess these tradeoffs in the context of the 2014–2016 marine heatwave, which

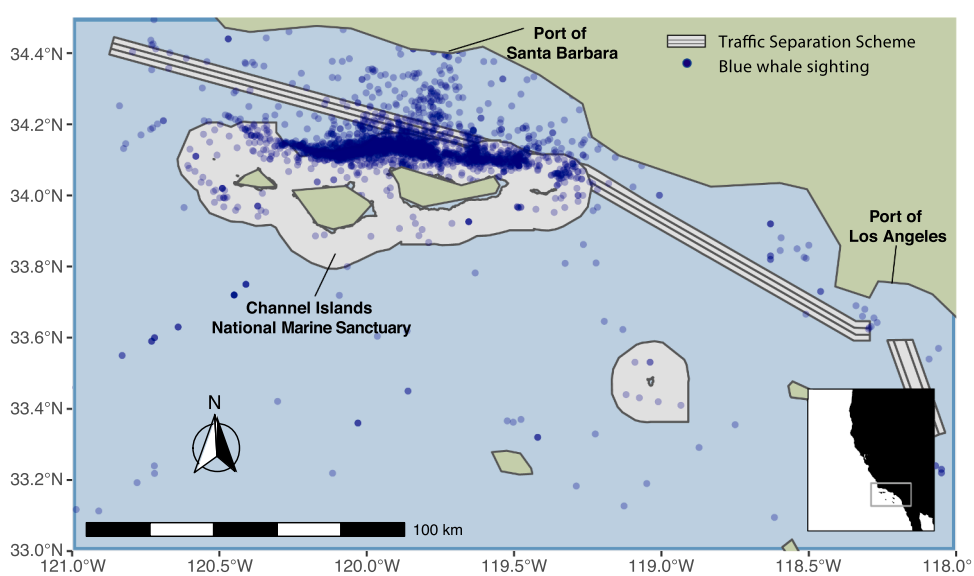

Fig. 1. Map of the Southern California Bight (SCB), USA, which encompasses the Channel Islands National Marine Sanctuary, a foraging hotspot for blue whales, and a Traffic Separation Scheme (TSS) delineating shipping lanes for transiting vessels. Blue dots indicate blue whale sightings compiled from several sources (see Table S1).

created changes in ocean conditions that persisted for several years [6]. As human pressures accelerate and climate change continues to drive unprecedented oceanic changes, there is a pressing need to assess how tradeoffs between conservation goals and human activities may vary under different environmental contexts, and identify management strategies that balance the needs of both people and species conservation.

2. Methods

2.1. Overview

We focused our analyses on lethal ship collisions with blue whales within the Traffic Separation Scheme, which delineates shipping lanes for transitting vessels, in the Southern California Bight (Fig. 1). We combined information on predicted blue whale habitat conditions, observed blue whale sightings from multiple platforms (Table S1), and vessel speed reduction management (10 knot speed limit) scenarios to conduct a tradeoff analysis between whale protection and shipping activity. The fixed strategy was compared to two DOM strategies that were triggered based on predicted whale habitat conditions (see *Management strategy scenarios*). Whale habitat conditions were obtained from published estimates within the study area derived from an ensemble species distribution model and are available daily in near-real time (see *Dynamic species distribution model*). Hindcast performance of the fixed and DOM strategies, measured as percentage of whales protected by vessel speed reduction periods, was evaluated from 2002 to 2018, as well as before, during, and after the 2014–2016 marine heatwave, using observed blue whale sightings data (see *Hindcast evaluation of management strategies*).

2.2. Dynamic species distribution model

Daily, year-round predictions of blue whale habitat conditions from 2002 to 2018 in the study area were generated from an ensemble species distribution model [27]. The model quantifies blue whale habitat preferences by relating relocation data from 104 satellite-tracked blue whales [26] to daily 3-dimensional oceanographic data [37,38]. Extensive cross-validation and validation using an independent dataset indicated strong predictive performance of the blue whale distribution model [27]. Model output provides daily predictions of blue whale habitat conditions valued from zero to one (lowest and highest habitat suitability, respectively), and has been used to quantitatively estimate ship strike risk to blue whales within the study region [39]. Daily, near-real time data from this model are publicly available at https://coastwatch.pfeg.noaa.gov/projects/whalewatch2/whalewatch2_map.html.

2.3. Management strategy scenarios

The fixed strategy implements a vessel speed reduction period from July 1st-November 30th each year irrespective of environmental conditions. The July-November period was chosen based on the implementation of a multi-year incentive-based vessel speed reduction program in the TSS beginning in 2014 (*see* https://channelislands.noaa.gov/management/resource/ship_strikes.html). The daily strategy implements a vessel speed reduction period if whale habitat suitability in the TSS exceeds a specified threshold on any given day. In this scenario, the vessel speed reduction period could be in effect one day, and removed the next day. The seasonal strategy implements a semi-continuous speed reduction period that is initiated when whale habitat suitability within the TSS exceeds the threshold for at least one week, and is removed when habitat suitability falls below the threshold for at least one week. We assessed 20 threshold values for habitat suitability at 0.05 intervals from 0 to 1. An example of how each strategy was implemented for a given habitat suitability threshold is depicted in Fig. 2.

2.4. Hindcast evaluation of management strategies

We compared the hindcast performance of the three management

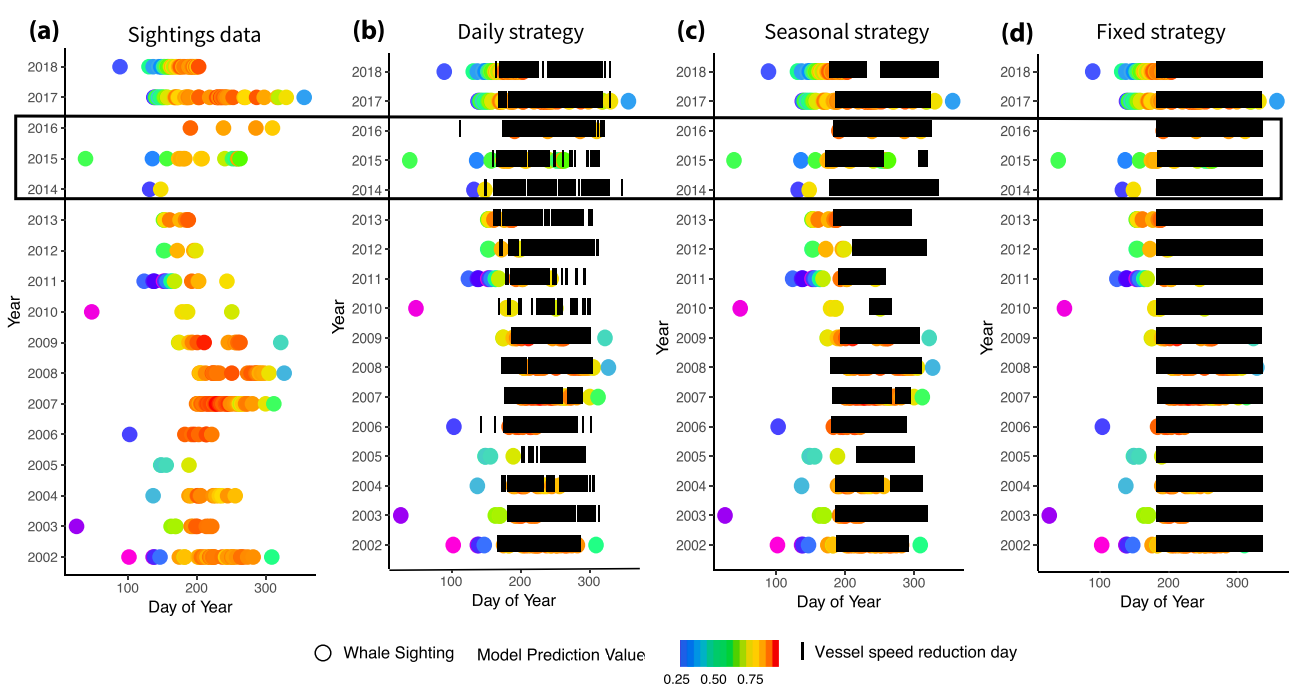

Fig. 2. (a) Daily distribution of blue whale sightings within the Traffic Separation Scheme from 2002 to 2018. Colors represent the predicted habitat suitability value within the shipping lane on a 0–1 scale from the blue whale distribution model. (b–d) Days of the year where a vessel speed reduction period was implemented (vertical black line) based on (b) the simulated daily DOM strategy with a threshold habitat suitability value of 0.8 (chosen for demonstration purposes), (c) the simulated seasonal DOM strategy with a threshold habitat suitability value of 0.8, and (d) the fixed strategy of a July–November vessel speed reduction period. The years of the 2014–2016 marine heatwave are outlined in black.

strategies from 2002 to 2018 using a compilation of historical blue whale sightings data from five systematically and three opportunistically collected datasets (Table S1), totaling 3413 blue whale sightings including 1313 sightings recorded inside the TSS used for analyses (Fig. 1). We used the sightings data to evaluate intra- and interannual variability in blue whale presence in the TSS. In addition, we used the sightings data to evaluate the percentage of whales in the TSS over the 17-year study period that would have been protected from shipping if a vessel speed reduction had been enforced under each management strategy. To check for potential bias derived from the opportunistic data, we also re-ran our analyses using only systematically-collected data (Fig. S1).

Each strategy was assessed using two metrics: the percentage of whales sighted within the vessel speed reduction period, and the percentage of shipping days with no speed restrictions (i.e., absent a vessel speed reduction period). The percentage of whales sighted within the vessel speed reduction period was calculated by dividing the total number of whales sighted in the TSS during any vessel speed reduction period during the 17-year study period by the total number of sighted whales in the TSS over the 17 years, multiplied by 100. The percentage of shipping days with no speed restrictions was calculated by subtracting the total number of vessel speed reduction days implemented during the 17-year period divided by the total number of days during the 17-year period (i.e., 365 × 17) from one, multiplied by 100.

These metrics were then plotted against one another in order to quantify potential tradeoffs. To assess how the strategies performed during normal versus anomalous environmental conditions caused by the 2014–2016 marine heatwave, this analysis was re-run for each strategy for the five years before (2009–2013) and the five years during and immediately after the marine heatwave (2014–2018) when anomalously high sea surface temperatures persisted [6].

3. Results

3.1. Intra- and interannual variability in blue whale presence

Both sightings data and the blue whale distribution model output confirmed that the fixed strategy – a vessel speed reduction period from July to November – spans the typical range of time when blue whales are most likely to be present in the TSS shipping lane (Fig. 2). 78.1% of the sightings occurred within the July-November speed reduction period, and the average predicted habitat suitability value for blue whales during those months was 0.84 (on a scale of zero to one) over the 17-year study period. However, 21.9% of whale sightings occurred outside the fixed speed reduction period, and while predicted habitat suitability values averaged 0.57 outside the fixed speed reduction period, values could be as high as 0.89, particularly in the years during and after the 2014–2016 marine heatwave (Fig. 2).

3.2. Performance of dynamic ocean management strategies

The percentage of whales expected to be protected from shipping traffic was lower with the July-November fixed strategy compared to both the daily and seasonal DOM strategies (Figs. 3 and 4). Even when the DOM strategies were not initiated until high habitat suitability threshold values were reached (e.g., 0.75), both the daily and seasonal strategies outperformed the fixed strategy (Fig. 3).

The daily and seasonal DOM strategies outperformed the fixed strategy across a large range of threshold values (Fig. 4). The tradeoff curves resulting from the daily and seasonal DOM strategies were qualitatively similar (Fig. 4), a result which remained consistent when the percentage of whales protected estimate was based solely on the systematic sightings data (Fig. S1). In comparison to the fixed strategy, both DOM strategies achieved similar or increased levels of whale protection with fewer vessel speed reduction days. For both DOM strategies, a habitat suitability threshold value of 0.8 led to equal percentages of whales receiving protection and days with vessel speed reductions. Hindcast evaluation revealed that the implementation of the seasonal or daily strategies would have protected an additional 6.4% or 10.7% of whales present in the shipping lanes, respectively, without requiring additional vessel speed reduction days, as compared to the fixed strategy (Fig. 4). When translated to the number of individual whales that would have received protection based on the sightings data, this results in an additional 84 or 141 whales protected under the seasonal and daily DOM strategies over the 17-year study period, respectively. Conversely, for the same number of whales receiving protection under the fixed strategy, the daily or seasonal strategies would have reduced the vessel speed reduction period by 9.9% or 10.2% (614 or 632 days) over the 17-year study period, respectively (Fig. 4). Furthermore, though there is interannual variability (Fig. S2), the daily and seasonal strategies

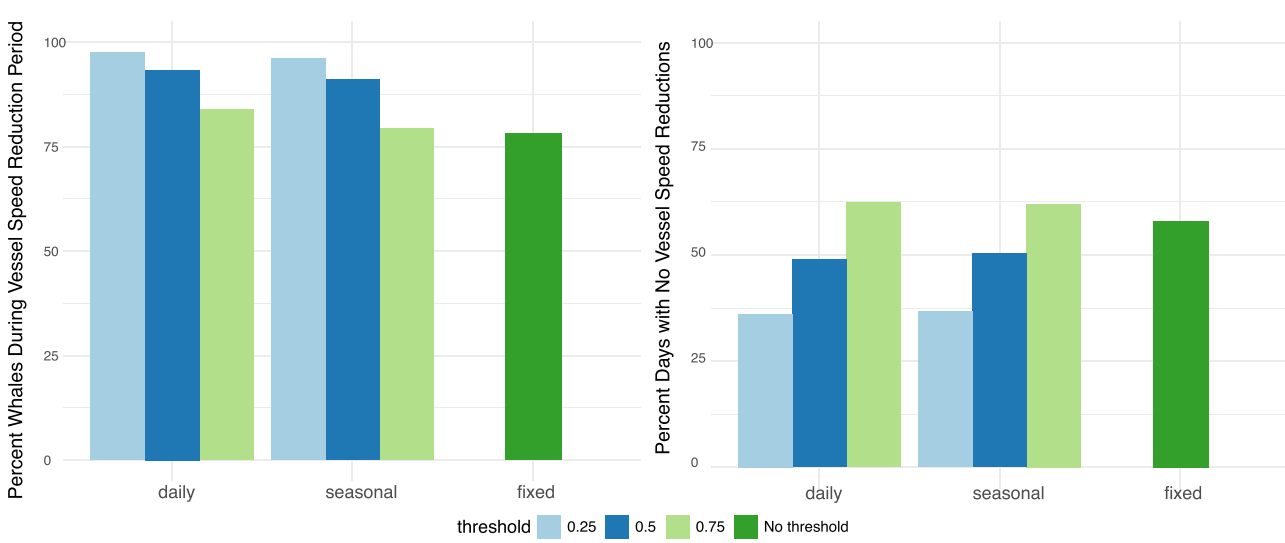

Fig. 3. The expected benefits of simulated dynamic ocean management (DOM) strategies are sensitive to the habitat suitability threshold selected, beyond which vessel speeds would be reduced. Here, three example habitat suitability thresholds (0.25, 0.5, 0.75) are selected for demonstration to examine differences in performance over the study period (2002–2018). Performance of the daily and seasonal DOM strategies are compared to the fixed strategy (assuming enforcement for all strategies). The left panel shows the percentage of blue whales expected to be protected from greater than 10 knot shipping speeds under each strategy; the right panel shows the percentage of days without vessel speed reductions under each strategy.

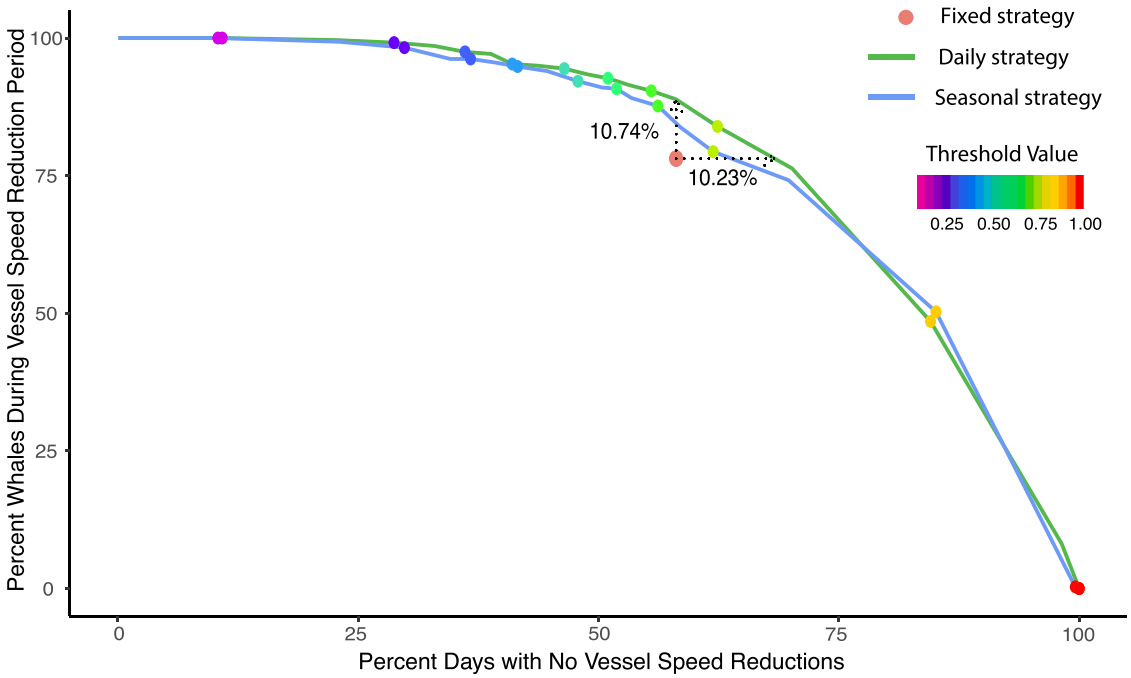

Fig. 4. Tradeoff comparison over the study period (2002–2018) between the percentage of days with unrestricted vessel speeds (x-axis) and the percentage of blue whales expected to be protected from greater than 10 knot shipping speeds (y-axis) for simulated seasonal (blue) and daily (green) dynamic ocean management strategies. Points along the curves reflect a range of threshold habitat suitability values, beyond which vessel speeds would be reduced to 10 knots (see text for details). The pink dot indicates how the July through November fixed strategy would perform, according to those same metrics, if enforced.

consistently achieved greater performance for at least one axis on the tradeoff curve compared to the fixed strategy regardless of the threshold value used (Fig. 4).

3.3. Effects of the marine heatwave

The benefit of both the daily and seasonal DOM strategies was accentuated during the anomalously warm conditions during and after the 2014–2016 marine heatwave (Fig. 5). Implementation of the daily management strategy in the five years prior to the heatwave would have protected an additional 16.2%, or 21, whales over the 5-year period without additional reductions to vessel speeds compared to the fixed strategy. However, during and after the heatwave, the daily strategy conferred protection to an additional 26.5% of whales, translating to 118 individuals over the 5-year period (Fig. 5). Conversely, for the same number of whales receiving protection under the fixed strategy, the

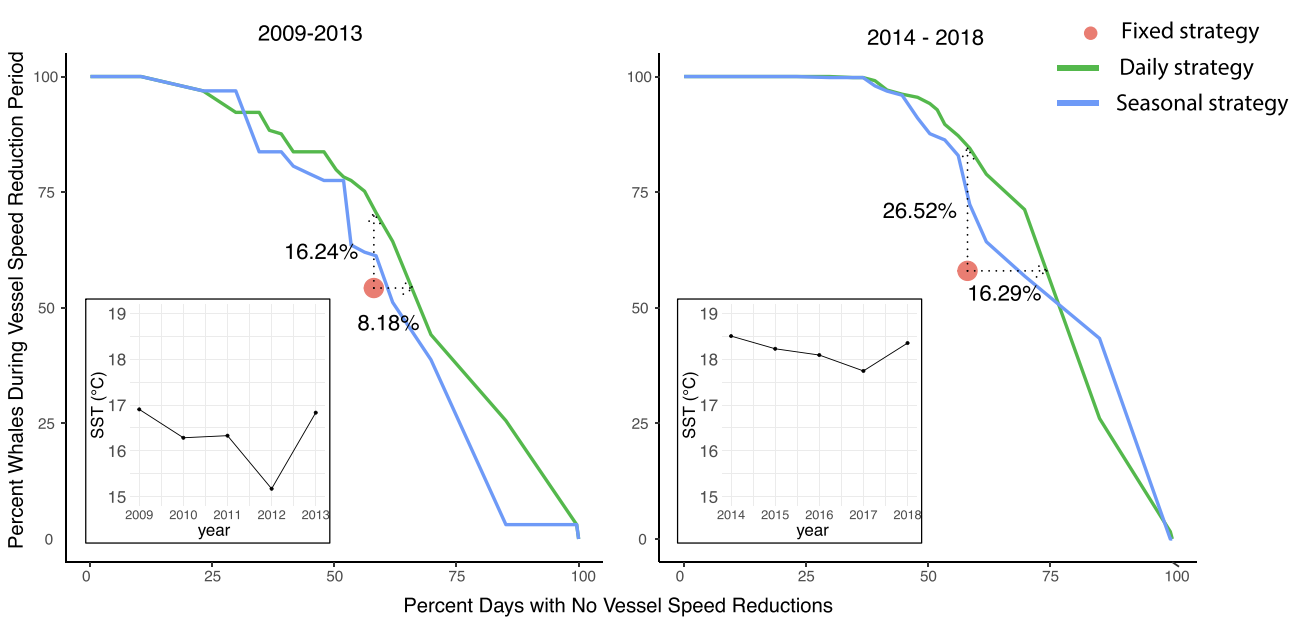

Fig. 5. Tradeoff comparison over the 5-year period before (2009–2013) and during and after (2014–2018) the marine heatwave between the percentage of days with no vessel speed reductions (x-axis) and the percentage of blue whales expected to be protected from greater than 10 knot shipping speeds (y-axis) for simulated seasonal (blue) and daily (green) dynamic ocean management strategies. The pink dot indicates how the fixed July through November strategy would perform, according to those same metrics, if enforced. Inset: Annual sea surface temperature (SST) averaged over the study area for each time period.

daily strategy would have reduced the vessel speed reduction period by approximately 8.2%, or 30 days, prior to the heatwave, versus 16.3%, or 60 days, during and after the heatwave.

4. Discussion

The confluence of climate extremes, directional climate change, and human activities pose special challenges for highly mobile and migratory species [40]. As migratory megafauna face increasing threats [41], identifying innovative management strategies that can adequately address tradeoffs between conservation goals and socio-economic needs are critical. Dynamic ocean management, in which management is adjusted in response to changing environments, animal distributions, and human activities, is increasingly proposed to balance such tradeoffs [9–11,42]. Moreover, as environmental conditions become more variable and extreme in the future [5,43], climate-ready management strategies must be implemented that remain robust under varying climate scenarios [44]. Our study highlights the utility of dynamic management strategies to balance tradeoffs between species conservation and human activities under a changing climate.

Over a 17-year period, we found a clear tradeoff between protecting whales and enabling unrestricted vessel activities. However, both DOM strategies improved outcomes compared to a fixed vessel speed reduction period. Specifically, seasonal and daily DOM strategies conferred an additional 6.4% and 10.7%, respectively, of whales that would have received protection for the same number of unrestricted shipping days as compared to the fixed strategy. Translated to between 84 and 141 individual whales over the 17-year study period that would have received protection based on the sightings data, this conservation benefit is substantial considering that the Potential Biological Removal limit for this blue whale population is 2.3 whales per year [17]. Conversely, for the same number of whales receiving protection, a reduction of 9.9–10.2% vessel speed reduction days (614 or 632 days) over the study period could have been achieved. This result emerged because the timing of whale migration and occurrence in the TSS varied substantially from year to year. Whereas the fixed strategy implemented a vessel speed reduction period at the same exact time each year, the seasonal and daily DOM strategies were responsive to the inherent interannual variability in the timing of whale occurrence. While there was significant interannual variability in the performance of management strategies, these improvements were especially marked in the years during and after the 2014–2016 marine heatwave occurring off of the U.S. west coast, when whale migrations occurred earlier than usual before the fixed vessel speed reduction period was enacted [28]. These results suggest that dynamic strategies are particularly valuable for coping with anomalous environmental conditions.

Our study contains several caveats. First, our estimates of the percentage of whales protected assumed mandatory compliance of the vessel speed reduction periods. However, current vessel speed reduction advisories in our study area are voluntary. Voluntary speed advisories have shown to have limited overall success in slowing down vessel speeds and reducing risk of lethal ship collisions compared to mandatory compliance measures [13,45], though in some studies voluntary measures as much as halved the probability of lethal strikes [46]. Under the assumption of compliance, we expect our estimates of percentage of whales protected under different management strategies to be conservative. This is because our analyses only considered whales that were sighted within the Traffic Separation Scheme, as opposed to the broader region where vessels transit through. It is also likely that many more whales occupied the TSS or surrounding area that remained undetected, in which case the percentage of whales that would have received protection from any vessel speed reduction scenario is underestimated. Ideally, monitoring systems would include multiple data streams to reduce both false positive and negative rates inherent to different monitoring methodologies, such as using a combination of sightings data, acoustic data, and predictive modeling. In addition, important tradeoffs may occur in efforts to simultaneously manage multiple protected species, such as humpback or fin whales co-occurring within the study area [24]. Here we focused our analyses on blue whales, as they are of greatest management concern with regard to ship strikes [17], but there is much promise for future studies that consider potential tradeoffs in managing multiple species of concern, as they may have different patterns of timing and occupancy.

On average, the seasonal DOM strategy performed similarly to the daily strategy (Fig. 4). This suggests that a strategy that is dynamic at fine timescales may not be necessary to achieve conservation and industry goals. Highly dynamic strategies that change daily with environmental conditions may offer the best opportunities of separating human activities from protected species [7], but in a study of dynamic ocean management to reduce fisheries bycatch, annual changes to fishery closures were able to achieve 80% of the successes of daily DOM strategies [42]. In addition, the daily DOM strategy evaluated in this study triggered a management response based on whale habitat conditions exceeding the assigned threshold for only one day, and therefore is subject to more noise from the environment, whereas the seasonal strategy was more conservative and required multiple consecutive days of habitat conditions exceeding the threshold.

Daily dynamic strategies also can be difficult to operationalize politically and technologically [47]. Observing a speed limit that is imposed and removed one day to the next is unlikely to be realistic for transiting ships who must plan their routes and time schedules in advance. To accommodate this, dynamic management areas to reduce strikes to North Atlantic right whales are implemented on short notice based on real-time whale observations, and remain in place for 15 days [13]. Intermediate strategies such as seasonal rather than daily or weekly closures could be more effective both in terms of political feasibility as well as industry cooperation. An alternative intermediate management strategy that we explored would be to update the timing of a seasonally-varying vessel speed reduction period using the date range of the previous year's whale sightings. Such an approach could be valuable for capturing incremental shifts in the timing of whale presence, for example due to long-term climate warming, without the need for a predictive habitat model, but performed poorly due to high interannual variability in whale sightings from one year to the next (Fig. S3). Regardless of the approach, dynamic ocean management does not supplant fixed management strategies, but rather offers complementary solutions [48]. For example, marine zoning with fixed boundaries is necessary for protecting resources that do not move in space, such as coral reefs, or for offering predictability necessary for industry planning. A combination of fixed and dynamic strategies may best address multiple tradeoffs in changing environmental and geopolitical climates [49].

In this study we have drawn on a tradeoff analysis to interrogate how actions taken to protect whales from lethal ship strikes restrict vessel speeds, which would increase costs to the shipping industry (cf. [14, 50]). This approach reveals a tradeoff curve, where the value of one axis cannot be increased without an additional cost to the other (e.g., a greater percentage of whales cannot be protected given an assumed number of days in which vessel activities are constrained), and allows for more explicit weighting of each service in management decisions [14]. Of course, compared to simple theory, an additional complexity in the context of our study stems from the fact that the costs are not borne by the same actors who reap the benefits (i.e., members of the shipping industry versus society writ large, given the high value placed on whale conservation, air quality, climate impacts, and ocean noise). This problem is common to tradeoffs in ecosystem management and marine spatial planning contexts [2], but not unresolvable with clear policy guidance and understanding of social preferences [51]. Tradeoff analyses such as those investigated here will be critical for evaluating the robustness of ocean management solutions to increasingly changing environmental, climatic, and socioeconomic conditions.

CRediT authorship contribution statement

Arjun Hausner, Briana Abrahms, Elliott L. Hazen, Jameal F. Samhouri: Conceptualization. **Arjun Hausner, Delgerzaya Delgerjargal**: Formal analysis. **Arjun Hausner, Briana Abrahms**: Investigation. **Briana Abrahms**: Supervision, Formal analysis. **Arjun Hausner, Jameal F. Samhouri, Elliott L. Hazen, Briana Abrahms**: Roles/Writing - original draft. Writing - review & editing – all authors.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2021.104565.

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