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Balancing marine species conservation with cost-effective renewable energy development

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Climate change is necessitating renewable energy development while contributing to shifting wildlife phenology and distribution. Renewable energy may require anthropogenic activity and wildlife to co-occur. Here we develop a framework to identify trade-offs between financial costs to developers and conservation, considering the critically endangered North Atlantic right whale (*Eubalaena glacialis*) and offshore wind energy development. By coupling an offshore wind energy construction simulation with a density surface model to quantify the number of right whales exposed to pile-driving noise under ten mitigation scenarios, we highlight mitigation measures, notably seasonal restrictions and noise attenuating devices, that can yield conservation value with minimal financial burden. As societies continue to refine and determine suitable financial and ecological trade-offs for development, frameworks like ours can be useful for exploring conservation challenges to ensure co-benefits for climate and biodiversity.

Climate change is impacting wildlife distributions and exacerbating human–wildlife conflicts[1]. Poleward wildlife range shifts in response to warming temperatures[2–4] are resulting in habitat loss for ecologically and economically important fish species[4] and changes in phenology of endangered marine mammals[5–7]. Converging with climate-induced changes in wildlife distribution, growing ocean industrialization is expected to increase risks to marine fauna[8–10]. For example, the potential for expanded shipping in an ice-free Arctic Ocean will increase the risk of ship strike to whales[11]. These changes in distribution, phenology and industrial activities complicate protections and recovery efforts[12], particularly for protected species whose management is primarily based on their migration patterns[13,14].

Mitigating climate change and minimizing human–wildlife conflicts are integral to a thriving 'blue economy', which is defined as the use of ocean resources for economic growth, social inclusion and the improvement of livelihoods, while ensuring ocean sustainability[15]. Renewable energy is an important tool to bolster the blue economy by supporting growing energy demands while mitigating climate change impacts through reductions in greenhouse gas (GHG) emissions[16]. The renewable energy industry contributes to economic growth through increases in career opportunities and investments in the supply chain and infrastructure; in addition, the industry can reduce air-pollution-related deaths and illnesses[17]. Globally, offshore wind energy production increased from 8,503 MW in 2014 to 72,663 MW in 2023[10] and is necessary to keep global warming below the target threshold increase of 2 °C (ref. 18). In the USA, US$17 billion were announced or invested in the offshore wind energy industry between 2014 and 2023[19]. Approximately 64% of coastal territorial waters of the USA have suitable wind speeds for offshore wind energy development, which if developed, would exceed the 2050 projected energy needs

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of the country[16]. However, many US offshore wind energy projects have struggled financially because of rising capital costs and variable interest rates[19], and are now faced with diminishing policy support[20]. As such, future development is constrained by cost, risk and uncertainty.

One of the costs incurred during wind energy development is measures designed to protect wildlife. Although offshore wind energy may help to mitigate a cause of conservation concern (that is, climate change), habitat change or loss due to renewable energy development can reduce biodiversity and change ecosystems[21]. Possible impacts of wind energy development on marine mammals may include auditory damage, displacement, increased ship strike risk, behavioural disruption, health impacts from stress and habitat alterations impacting prey species[22–24]. Although the impacts of pile-driving noise are documented for some marine mammal species[25,26], the distance and source levels that elicit disturbance behaviour are variable[26,27]. By contrast, the sensitivity of large whales to offshore wind construction is currently unknown, as most offshore wind projects have occurred in regions lacking high densities of these species.

All mitigation measures have a cost. Noise-reduction technologies (bubble curtains and double big bubble curtains) provide an acoustic barrier around pile-driving activity, reducing the area impacted by pile-driving noise. A double big bubble curtain, which can be re-used for each pile in a construction campaign, increases the project cost by approximately US$7 million (~7% of total project costs)[28]. In theory, when wildlife migration patterns are reliable, seasonal mitigation measures reduce the probability that protected species co-occur with pile-driving. They also may reduce the likelihood of construction delays or shutdowns, which occurs when specific protected species (for example, North Atlantic right whales, *Eubalaena glacialis*) are detected in a defined area surrounding pile-driving[29–31], resulting in sunk costs and an extension of the project duration (approximately US$805,000 per day in 2018[32–34]) that further increases costs. However, if seasonal restrictions cause a project to extend into a second year, the price of development substantially increases (approximately US$30 million in 2018[35]). Because of these costs, it behoves developers to schedule construction when right whale occurrence probability is low. Unfortunately, recently unexpected climate-driven changes in right whale distribution have complicated these efforts.

Trade-off analyses can be used to balance economic growth with species conservation. We developed a framework that assesses the costs and conservation benefits of mitigation measures for pile-driving noise. Although this framework is broadly applicable to exploring the optimization of benefits for wildlife and many ocean industries, we apply it to the critically endangered North Atlantic right whale in the first commercial-scale wind energy development in US waters (Rhode Island and Massachusetts/Rhode Island wind energy areas; hereafter wind energy areas) (Fig. 1a). Regular aerial surveys, documenting the distribution of whales and sea turtles began in the wind energy areas in 2011 (Fig. 1b). In 2013, the Bureau of Ocean and Energy Management designated the wind energy areas for development. Aerial surveys conducted from 2011 to 2015 documented low right whale abundance, especially in the summer months[36]. During the permitting process, historical migration patterns[37,38] were used to identify the summer and early autumn (May–November) as months when construction would have minimal co-occurrence with right whales[39,40]. However, in an era of climate change, right whale distribution has deviated from historical patterns[6,41,42]. Aerial surveys conducted after 2015 showed increasing right whale abundance throughout the years, including during the summer months when construction was scheduled to occur[36].

For our trade-off analysis, we used aerial survey data to develop a density surface model (Fig. 2) that captures the observed changes in right whale distribution in the wind energy areas. The results of this model are comparable to other models[40,43], but the temporal resolution is higher as required for scheduling construction. We use these predictions in a development simulation (Fig. 1c,d) to quantify the number of right whales exposed to noise levels associated with Level A and B takes under ten mitigation scenarios (that is, combinations of seasonal restrictions and additional noise attenuation systems; Table 1). The US Marine Mammal Protection Act (MMPA) defines Level A harassment as any act that has the potential to injure a marine mammal or marine mammal stock in the wild. Level B harassment is defined as any act that has the potential to disturb a marine mammal or marine mammal stock in the wild by causing a disruption of behavioural patterns[44]. We then evaluate the cost of each scenario in comparison with the level of protection afforded to right whales. Our approach is broadly applicable to other species, industries and mitigation scenarios, and can aid efforts to move renewable energy goals forward while conserving endangered species.

Results

We used a density surface model (Extended Data Table 1) fit with aerial survey data (Fig. 1b) to estimate the number of right whales exposed to sound levels associated with Level A and B takes during pile-driving activities under ten mitigation scenarios (Table 1 and Supplementary Table 1). Mitigation scenarios included combinations of seasonal restrictions and additional noise attenuation systems and were compared with the current schedule seasonal restriction scenario (hereafter, percentage change in takes). We used the literature to estimate the median, median +20% and median −20% radial distance that pile-driving noise would travel[45–47]. The cost of each campaign depends on the number of days required to drive 70 monopiles, which can vary as a result of weather conditions. We estimated the cost of each campaign assuming a daily rate of US$805,000 in 2018[32–34]. This cost includes a heavy-lift vessel (US$765,000), project resources (US$20,000) and two guard vessels (US$10,000 each). We also include a yearly cost of mobilization (US$30 million)[35]. We apply an additional cost of US$7 million for a double big bubble curtain[28].

Density surface model

We tested the ability of ten density surface models, to predict right whale density (Extended Data Table 1). The model with the most relative support included salinity, an interaction between sea surface temperature (SST) and 8-day period and an interaction between distance to the 30-m isobath and 8-day period (Extended Data Table 1). This model also had the highest area under the receiver curve (AUC) and explained 33.4% of the deviance (AUC = 0.89; Extended Data Table 1). There was a significant non-linear relationship between right whale density and all the variables in the model ($P < 0.05$ for each covariate; Extended Data Fig. 1). We found seasonal patterns in right whale density across all years (Fig. 2 and Extended Data Fig. 2). During the winter, right whale density was highest along the 30-m and 40-m isobaths and on Nantucket Shoals (Extended Data Fig. 2). Right whale density was high throughout the study area during spring, particularly along the 30-m and 40-m isobaths, but density also increased between winter and spring in the south-west portion of the prediction area (Extended Data Fig. 2). Density decreased during summer but remained high along the eastern side of the 30-m isobath and on Nantucket Shoals. Densities were lowest in the autumn and suggested that right whales would be found along the 30-m isobath (Extended Data Fig. 2). In general, these seasonal patterns were well represented within each year, with some notable exceptions. For example, the pattern of higher density in the summer months along the eastern side of the 30-m isobath and on Nantucket Shoals began in 2014 and predicted density was particularly high on Nantucket Shoals in 2017 and 2019 (Fig. 2 and Extended Data Fig. 3).

Trade-off analysis

The comparisons below express the percentage change in the predicted number of right whales exposed to noise associated with Level

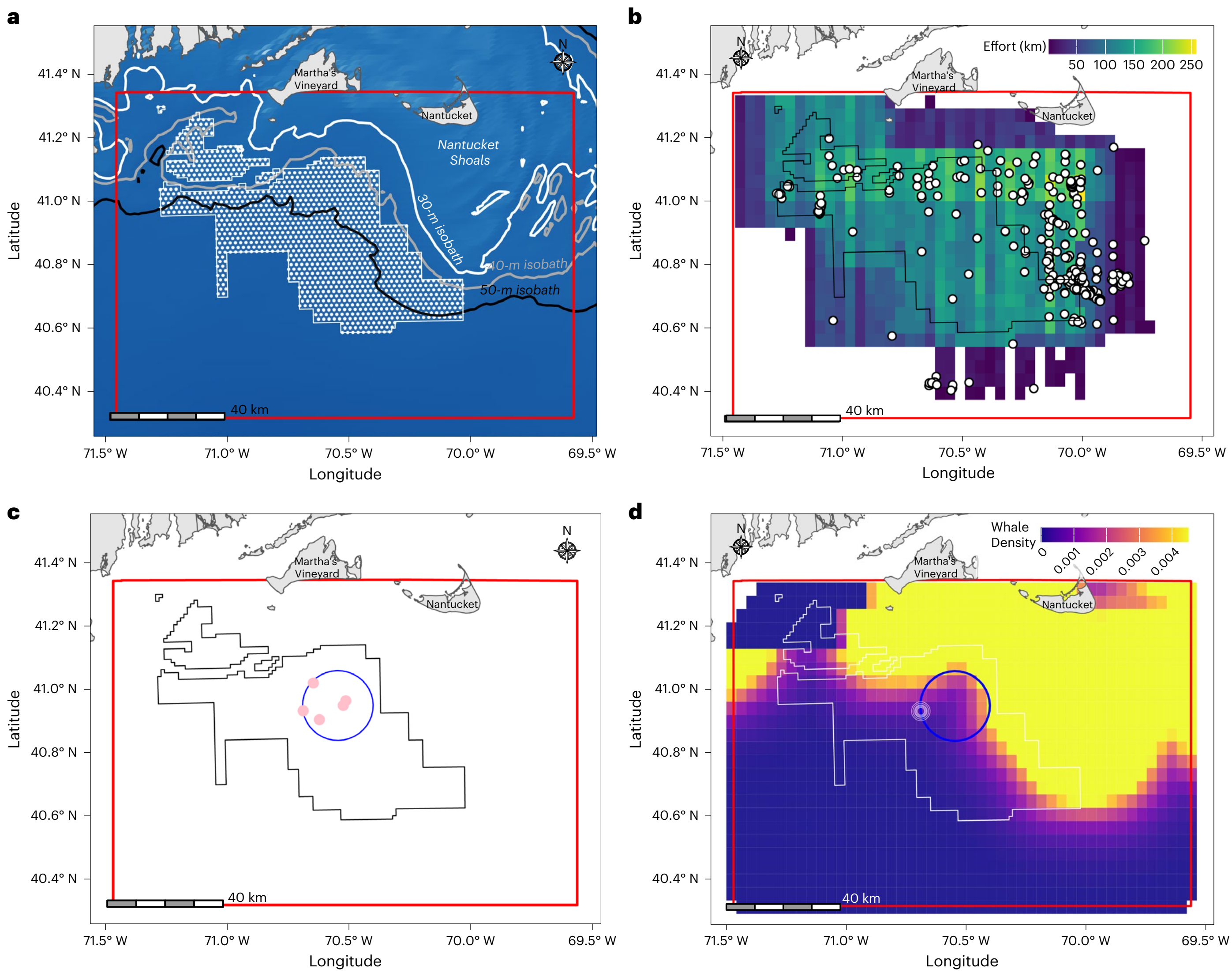

Fig. 1 | The Massachusetts/Rhode Island wind energy areas, aerial survey effort and right whale sightings and trade-off simulation example schematic. In **a**–**d**, the density surface model prediction area is outlined in red. **a**, The relevant isobaths are denoted in white (30 m), grey (40 m) and black (50 m), along with the simulated wind-farm layout for the Massachusetts/Rhode Island wind energy areas (white outline) with hypothetical turbines (white circles) spaced 1 nautical mile apart. **b**, New England Aquarium aerial survey effort (70,074 km), summarized in 4.6-km grid cells. White dots represent right whale sightings made during aerial surveys ($n = 600$ animals). **c**, The trade-off simulation began by selecting an area for development (blue circle; 468 km^2) and five turbines (pink dots) randomly chosen for pile-driving in the first 8-day period of the simulation. **d**, Right whale density summarized by grid cell, for the corresponding 8-day period, with the white circles indicating the Level A take ranges using 10 dB and 12 dB of noise attenuation. US geographic boundaries from the US States (Generalized) layer within the Esri Data & Maps suite (https://www.arcgis.com/home/item.html?id=c66cec727b7b4ef99e470e50b9c98663, 2004), Esri, TomTom, USGS, FAO, NOAA, NRCan. Offshore wind energy commercial lease boundaries and right-of-way grants were obtained from the Offshore Wind Lease Outlines database managed by the Bureau of Ocean Energy Management (https://www.arcgis.com/home/item.html?id=709831444a234968966667d84bcc0357), Esri, TomTom, Garmin, USGS, FAO, NOAA, EPA, USFWS, Bureau of Ocean Energy Management (BOEM), Office of Renewable Energy Programs (OREP).

A and B takes and development costs, when compared with the current schedule seasonal restriction scenario (estimated at a construction cost of US$95.795 million; Fig. 3 and Supplementary Fig. 1). Increases in cost result from adverse weather conditions, increasing the number of days required to complete construction or the cost of a double big bubble curtain. Allowing pile-driving in all months (that is, no seasonal restriction) increases the predicted number of right whales exposed to Level A take noise thresholds by 236% and increases the cost by US$6.44 million. When compared with the current schedule seasonal restriction scenario, no seasonal restriction and additional noise attenuation results in an increase in Level A takes by 13% and the cost increases by US$13.44 million. There is a reduction in Level A takes, but a US$6.44 million increase in costs, when the current schedule seasonal restriction scenario is compared with the June–December (24% reduction in Level A takes) and June–November seasonal restriction scenarios (23% reduction in Level A takes). If a double big bubble curtain is used there is an additional US$7 million cost over the current schedule seasonal restriction scenario[28], but the risk reduction is large and similar among pile-driving options that include a seasonal restriction (current schedule seasonal restriction and additional noise attenuation = 66% reduction in Level A takes, US$7 million cost increase; June–December and additional noise attenuation = 74% reduction in Level A takes, US$13.44 million cost increase; May–November and additional noise attenuation = 67% reduction in Level A takes,

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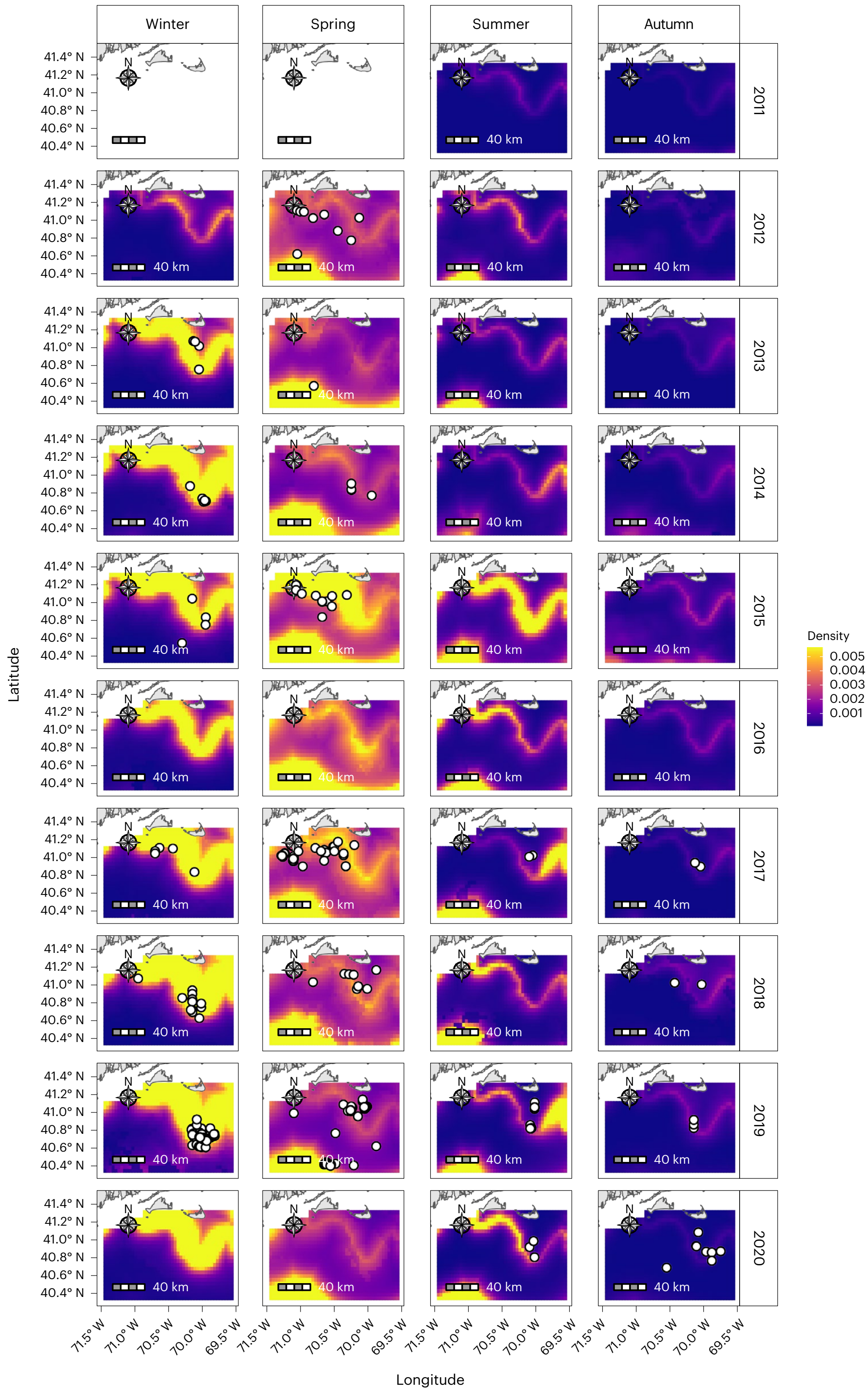

Fig. 2 | Right whale density predictions per 1 km². Right whale density was estimated using a density surface model fit with aerial survey data collected between 2011 and 2020 using $n = 14{,}410$ survey segments derived from 137 aerial surveys. Survey segments, the unit of analysis, were chopped according to the segment chopping methods described in Supplementary Information, with 89% of the segments meeting the target length of 4.6 km. The model with the most support used distance to the 30-m isobath × period, SST × period and salinity as predictors. Panels show the annual seasonal average right whale density based on predicted 8-day densities. White dots show right whale sighting locations from the aerial surveys. There was a significant non-linear relationship between right whale density and all the variables in the model ($P < 0.05$ for each covariate; Supplementary Fig. 1). US geographic boundaries from the US States (Generalized) layer within the Esri Data & Maps suite (https://www.arcgis.com/home/item.html?id=c66cec727b7b4ef99e470e50b9c98663, 2004), Esri, TomTom, USGS, FAO, NOAA, NRCan. Offshore wind energy commercial lease boundaries and right-of-way grants were obtained from the Offshore Wind Lease Outlines database managed by the Bureau of Ocean Energy Management (https://www.arcgis.com/home/item.html?id=709831444a234968966667d84bcc0357), Esri, TomTom, Garmin, USGS, FAO, NOAA, EPA, USFWS, Bureau of Ocean Energy Management (BOEM), Office of Renewable Energy Programs (OREP).

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Table 1 | Summary of pile-driving window, noise attenuation and Level A and B take ranges (radial distance) for each mitigation scenario used in the trade-off analysis

Mitigation scenario	Noise attenuation	Level A radial distance	Level B radial distance
No seasonal restriction	10 dB	2.74 km (2.18, 3.28)	6.07 km (4.84, 7.26)
No seasonal restriction and additional noise attenuation	12 dB	1.60 km (1.27, 1.91)	2.74 km (2.19, 3.28)
Current schedule seasonal restriction (May–December)	10 dB	2.74 km (2.18, 3.28)	6.07 km (4.84, 7.26)
Current schedule and additional noise attenuation	12 dB	1.60 km (1.27, 1.91)	2.74 km (2.19, 3.28)
May–November seasonal restriction	10 dB	2.74 km (2.18, 3.28)	6.07 km (4.84, 7.26)
May–November seasonal restriction and additional noise attenuation	12 dB	1.60 km (1.27, 1.91)	2.74 km (2.19, 3.28)
June–November seasonal restriction	10 dB	2.74 km (2.18, 3.28)	6.07 km (4.84, 7.26)
June–November seasonal restriction and additional noise attenuation	12 dB	1.60 km (1.27, 1.91)	2.74 km (2.19, 3.28)
June–December seasonal restriction	10 dB	2.74 km (2.18, 3.28)	6.07 km (4.84, 7.26)
June–December seasonal restriction and additional noise attenuation	12 dB	1.60 km (1.27, 1.91)	2.74 km (2.19, 3.28)

Each scenario uses a single bubble curtain unless additional noise attenuation is specified indicating a double big bubble curtain was used. The median radial distance to take thresholds is indicated for Level A and B takes; variation in radial distances (±20% of the median).

US$7 million cost increase; and June–November and additional noise attenuation = 74% reduction in Level A takes, US$13.44 million cost increase). The change in risk for exposure to Level B takes was similar to Level A takes (Fig. 3 and Supplementary Fig. 1). However, allowing construction in all months while using a double big bubble curtain reduced the predicted number of right whales exposed to noise exceeding Level B take thresholds, differing from the impact on Level A takes (no seasonal restriction and additional noise attenuation = 44% reduction in Level B takes), and we found large variability and often an increase in the predicted number of right whales exposed to Level B takes (Fig. 3 and Supplementary Fig. 1).

The magnitude of variation around the predicted number of right whales exposed to noise exceeding take thresholds depends on the temporal and spatial location of the wind farm (Figs. 4 and 5). In 2018, standard deviations of right whale density estimates were high in the winter months (Extended Data Fig. 3), when right whale abundance was high. The higher standard deviation during this season leads to relatively high variation in the predicted number of right whales exposed to takes for the no seasonal restriction scenario (Figs. 3–5), which is the only scenario that allows construction during the winter months. In comparison, density estimates in the wind energy areas in the summer and autumn were more precise, when right whale abundance was lower, resulting in increased precision in the predicted number of right whales exposed to takes (Figs. 3–5). There was also high variation in the predicted number of right whales exposed to noise exceeding take thresholds in the winter months depending on the spatial location of the wind farm (for example, wind farms in the south-west portion of the wind energy areas have lower right whale density predictions than those in the north-west).

Variations in the radial distance threshold did not impact the percentage change in the predicted number of takes when comparing the mitigation scenarios with the current schedule seasonal restriction, rather they only influenced the absolute number of takes (Extended Data Figs. 4–7). Therefore, the conclusions of our trade-off analysis were consistent across radial distance thresholds.

Discussion

Developing offshore renewable energy will help meet increasing energy demands and potentially increase economic growth, mitigate climate change and help achieve a thriving, environmentally sustainable, blue economy. To achieve these goals, the impacts of offshore development on vulnerable species must be minimized. Ideally, wildlife mitigation measures would be optimized to yield maximum conservation value while incurring minimal financial burden.

We developed a framework that assesses the development costs and conservation benefits associated with pile-driving noise mitigation measures. Our analysis allows for a high resolution, spatially and temporally explicit assessment of wind-farm construction impacts on local wildlife, extending beyond the broad considerations of previous trade-off analyses[48–50]. In the USA, the permitting process quantifies the number of animals exposed to potentially harmful impacts by counting the number of takes. Therefore, we used exposure to Level A and B takes as our measure of conservation value and found our results to be broadly agreeable with current authorizations. Although our case study required several simplifying assumptions (discussed below), our framework allows interested parties to adjust the assumptions, determine the conservation impacts of development and minimize costs.

Under our assumptions, we identified several scenarios where increased conservation value came with minimal additional costs. Both incorporating additional noise attenuation (that is, double big bubble curtain) and seasonal restrictions, reduced the number of whales predicted to be exposed to Level A takes when compared with the current schedule seasonal restriction scenario (Fig. 3). A double big bubble curtain used with seasonal restrictions provides the most conservation benefit and results in a cost increase of US$7–13.44 million over the current schedule seasonal restriction scenario, due to the cost of the additional noise attenuation device and additional construction time needed resulting from adverse weather conditions[28]. The additional US$7 million is only 7% of the total cost of the current schedule seasonal restriction scenario. Increased right whale protections can also be achieved through seasonal restrictions, even without the use of additional noise attenuation. We show that no seasonal restrictions result in large increases in the number of right whales predicted to be exposed to Level A and B takes because of the seasonal whale occurrence patterns indicated by our density surface model (Fig. 2 and Extended Data Fig. 2).

The possibility for mitigation measures to extend pile-driving into a second year is an important consideration for developers as it would result in a minimum US$30 million cost increase. In our simulation, even under the most limiting seasonal restrictions, construction can be completed within 1 year. Therefore, the additional costs of further seasonal restrictions are relatively minimal, increased only by season-specific weather delays.

There is a risk that a campaign could extend into a second year because of work stoppages caused by whale detections made by protected species observers or supply chain and vessel mobilization issues. Right whale detections made from the pile-driving vessel trigger a mandated work stoppage until protected species observers have not detected a right whale from the vessel for at least 30 minutes[51]. Reports by protected species observers in the study area[52,53] indicate that during the construction season (May–December) stoppages for marine mammals were minimal, and that periods of low visibility, which are included in our analysis, cause most delays. Including the delays caused by marine mammal detections would require several additional steps and therefore have not been included in our analysis. These steps would include estimating platform-specific detection probabilities for visual and acoustic monitoring, contextualizing the acoustic data with

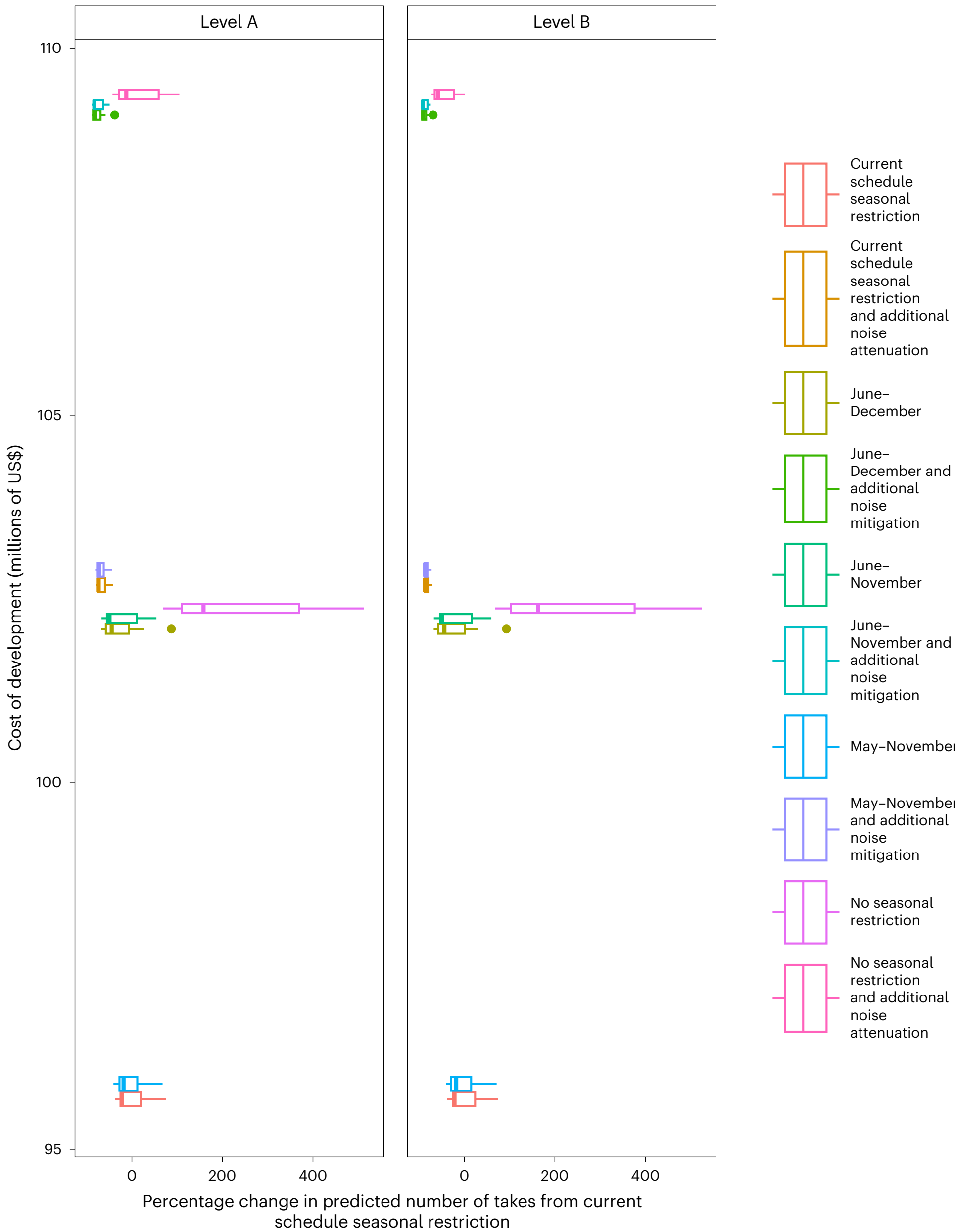

Fig. 3 | Several mitigation scenarios provide an increase in right whale protections (reduction in percentage change in the predicted number of takes from the current schedule seasonal restriction) with minimal additional financial costs. Mitigation scenarios vary by colour. The box plots show median values and the lower and upper hinges correspond to the first and third quartiles. The upper (lower) whisker extends to the largest (smallest) value no further than 1.5× the interquartile range. Data beyond the end of the whiskers are outliers. Box plots summarize values from $n = 10$ wind energy development campaigns. For each campaign, 70 turbines were driven, with each turbine measured ten times to incorporate the variation from the ten right whale density surface model simulations.

information about whale behaviour, background noise and acoustic propagation conditions[54] and fine-scale vessel tracking to determine the search area covered.

Exceedance of the number of legally permitted takes can cause additional delays and costs from operational adjustments, permit modifications or project shutdowns[55]. Therefore, identifying cost-effective solutions to minimize right whale takes during project development both protects marine mammals and the project. Delays and unexpected costs may also result from supply chain complications, material cost increases and changes in the political landscape[56]. For current wind energy development projects, these complications have resulted in costs ranging from US$50 million a week to US$600 million total[57]. In this context, the mitigation costs to reduce impacts on critically endangered species is minimal. Additionally, we did not include the financial value of right whales, provided through ecosystem services or their intrinsic value, in our trade-off analysis.

Our trade-offs framework is widely applicable to other species, sectors within the blue economy and mitigation scenarios. However, we focused on a small fraction of the operational costs for wind energy production and risks to marine taxa (that is, mitigation measures that reduce pile-driving noise impacts on right whales). Other possible risks to right whales associated with wind energy development were not considered, including ship strikes and changes to habitat that may affect right whale prey resources[58]. In addition, mitigation measures and understanding the impacts of offshore wind development become more complex if several species are considered. Owing to

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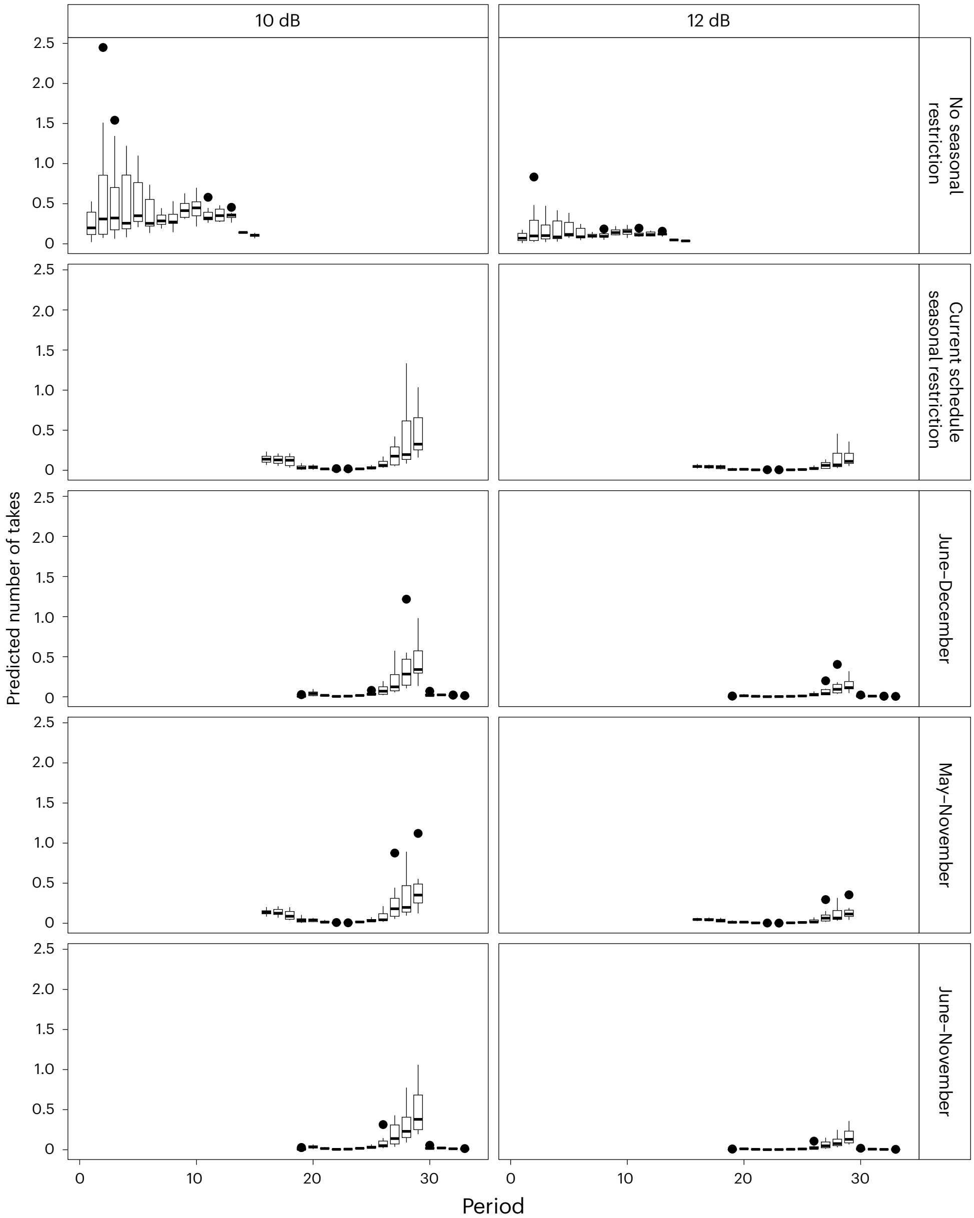

Fig. 4 | The predicted number of right whales estimated to be within the Level A take radius during a wind energy development campaign in each 8-day period. The range of predicted number of Level A takes shown here includes takes estimated using the standard radial distances. The mitigation measures in the left panel include 10 dB of noise attenuation; the right panel includes 12 dB of noise attenuation. The box plots show median values and the lower and upper hinges correspond to the first and third quartiles. The upper (lower) whisker extends to the largest (smallest) value no further than 1.5× the interquartile range. Data beyond the end of the whiskers are outliers. Box plots summarize values from $n = 10$ wind energy development campaigns per week. For each campaign, within each 8-day period, a maximum of five wind turbines were driven when weather allowed, with each turbine measured ten times to incorporate the variation from the ten right whale density surface model simulations.

the asynchronous habitat use of cetacean species in the wind energy areas[59], the seasonal restrictions that minimize the impacts on right whales could simultaneously increase the risk for other endangered species. These complexities further increase if development is scaled up from the wind energy areas to the roughly 65% of the Atlantic seaboard with wind conditions suitable for energy production, which wholly overlaps the right whale range. Finally, the ability to conduct the analysis is contingent upon the availability and amount of the data required to fit a species distribution model and an understanding of the effectiveness of the mitigation measure. For example, since the wind energy areas were designated, there has been relatively consistent aerial survey effort. These surveys also incur a financial cost (approximately US$500,000 per year), albeit minimal relative to the other costs we have detailed. Lower levels of survey effort will decrease the precision in density estimates, thereby reducing the utility of the results.

Humans are increasingly looking to the ocean for renewable energy to mitigate the broad and chronic impacts of climate change. Although offshore wind energy presents an opportunity to reduce GHG emissions and slow climate change, it also contributes to increasing ocean industrialization, which may have local and acute impacts on wildlife. We show that strong mitigation requirements are necessary to reduce risks to protected species. It is also important to understand and moderate the human–wildlife conflicts that result from development. To achieve a thriving blue economy, namely one that balances economic growth with sustainable practices, more open-source quantitative tools that assess the trade-offs between wildlife conservation and ocean industries are required.

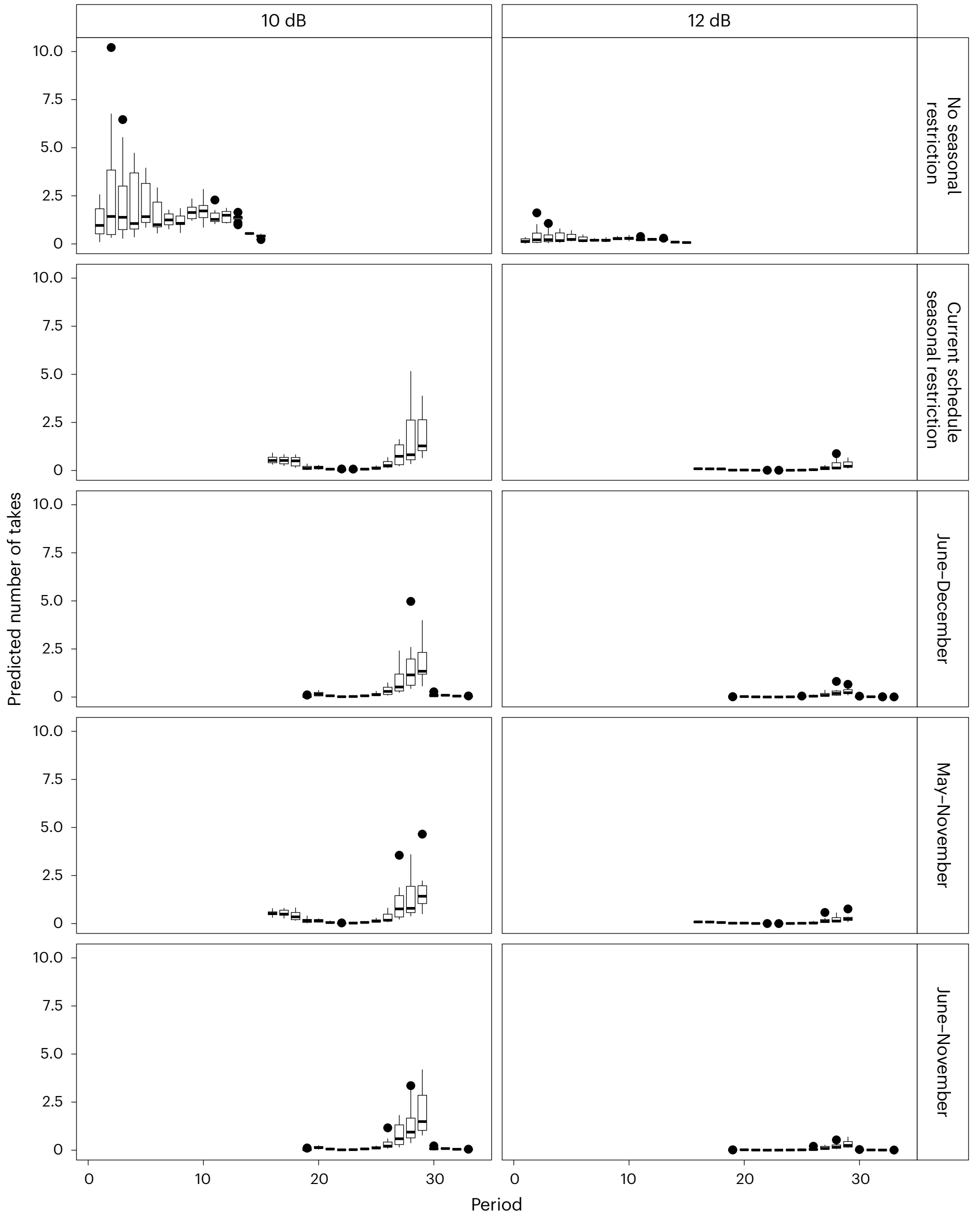

Fig. 5 | The predicted number of right whales estimated to be within the Level B take radius during a wind energy development campaign in each 8-day period. The range of predicted number of Level B takes shown here includes takes estimated using the standard radial distances. The mitigation measures in the left panel include 10 dB of noise attenuation; the right panel includes 12 dB of noise attenuation. The box plots show median values and the lower and upper hinges correspond to the first and third quartiles. The upper (lower) whisker extends to the largest (smallest) value no further than 1.5× the interquartile range. Data beyond the end of the whiskers are outliers. Box plots summarize values from $n = 10$ wind energy development campaigns per week. For each campaign, within each 8-day period, a maximum of five wind turbines were driven when weather allowed, with each turbine measured ten times to incorporate the variation from the ten right whale density surface model simulations.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-026-02696-9.

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Methods

Estimating whale density

North Atlantic right whale sightings data were obtained from the North Atlantic Right Whale Consortium. Access to these data is subject to the data use policies and approval procedures of the Consortium. Researchers may request access to the data through the Consortium data request process at https://www.narwc.org/accessing-narwc-data.html.

Data collection and preparation. Whale sightings were collected during aerial surveys, flown approximately twice monthly, in Southern New England between 2011 and 2020 (Fig. 1b). Aerial surveys were flown at a ground speed of 185 km h^{-1} and an altitude of 305 m, in a Cessna Skymaster 337 O-2A aircraft. Trackline effort and environmental conditions were recorded every 2–5 s. Two observers, one on either side of the aircraft, scanned their field of view for whales. Sightings were recorded when they were perpendicular to the aircraft. Marks on the wing struts were used to record the estimated distance of the sighting from the trackline. When right whales were sighted, the plane diverted from the trackline to obtain photo-identification data for monitoring use of the area by individual whales.

To use the aerial survey data in density surface models, sections of aerial survey tracklines with uninterrupted survey effort were separated into approximately 4.6-km segments to correspond with the resolution of remotely sensed environmental data. The number of whale sightings and the number of whales in a group were summarized for each segment.

Density surface model

To estimate whale density, we used a multistep modelling approach. The first step included fitting a detection function and estimating the effective strip width. The details of this process can be found in ref. 36. Because these surveys were flown in closing mode (that is, the team diverted from the trackline to obtain photographs of individual whales), some whales were observed when the plane was not on the trackline. To adhere to the assumptions of distance sampling, the detection function was fit only with whales sighted from the trackline. By contrast, the spatial model (described below) was fit with all animals regardless of whether the animal was detected when the plane was on or off the trackline. The Distance package in R was used to fit a detection function with a hazard rate model[60]. The second step in the modelling process included fitting generalized additive models (GAMs) to capture the relationship between the number of whales observed on a segment and oceanographic predictor variables (described below). We used a Tweedie distribution and fit the models using the dsm package in R (ref. 61). Parameter estimates were optimized using restricted maximum likelihood. Thin plate regression splines were used to model the relationship between individual environmental variables and right whale density. Relationships between whale density and interactions between variables were modelled using tensor splines. Density (D) was estimated as follows:

$$D_i = (n_i/L_i) \times \frac{1}{2}\,(\mathrm{ESW}) \times g(0)$$

Where n is the number of animals on segment i and L is the length of the segment (km). ESW is the effective strip half-width estimated from the detection function. We assumed perfect detection on the trackline ($g(0) = 1$). An offset was used in the GAMs to include the natural log of the effective area searched.

We used density surface models to estimate whale density as a function of oceanographic variables (Extended Data Table 1). Southern New England is an oceanographically complex region that includes a 30-m isobath along the northern edge of the study area that outlines Nantucket Shoals (Fig. 1a). The 30-m, 40-m and 50-m isobaths that frame the Shoals have topographically rectified currents which coalesce species such as calanoid copepods, Atlantic surf clams, ocean quahogs, gammarid amphipods, and a wide diversity of mollusk, crustacean and echinoderm species[62,63]. The 30-m isobath is associated with a strong tidal front which promotes nutrient mixing and phytoplankton blooms, but the tidal front may preclude the aggregation of *Calanus finmarchicus*, the primary prey of right whales[62,63]. Right whales have been observed feeding in this area, indicating that they may be supplementing their diet with other copepods such as *Pseudocalanus* spp. and *Centropages typicus*, both of which have also been found in southern New England[63]. Right whales have been observed over a wide range of depths and their preferred depths vary by habitat. In the Gulf of Maine, right whales regularly occur in waters 100–200 m deep. However, in Cape Cod Bay, which is a prolific spring feeding ground, right whales occur in waters that are only 18–60 m deep. We used 0.00083° resolution depth data from the Northeast Coastal Relief Model (v.1)[64] as a predictor variable in our density surface models. We calculated the distance from each segment midpoint to the 30-m, 40-m and 50-m isobath using the marmap package in R (refs. 61,65). In the absence of right whale prey data suitable for our study, we used chlorophyll *a* concentration because it is an indicator of primary production, which should be broadly indicative of secondary production and the zooplankton species, such as *C. finmarchicus*, that are targeted by right whales. We used Aqua MODIS global mapped chlorophyll data sampled at 8-day intervals at a 4-km spatial resolution[66]. In Cape Cod Bay, abundance of *C. finmarchicus* and *C. typicus*, a second right whale food source, were found to be correlated with salinity[67]. We obtained 4-day salinity data on a 1/4° grid from the Multi-Mission Optimally Interpolated Sea Surface Salinity Global Dataset (v.1)[68]. Previous studies have found the winter distribution of right whales to be largely determined by SST, although the mechanism for this influence is unclear[43]. We obtained daily SST data on a 0.01° grid from the GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis (v.4.1)[69]. All oceanographic variables were standardized on a 4.6-km grid, over 8-day periods. Oceanographic data were associated with the midpoint of each trackline segment. We created 8-day, 4.6-km prediction grids over the spatial extent of the prediction box (Fig. 1).

We assessed model fit by visually inspecting quantile–quantile plots and using the root mean squared error. We compared models using the area under the curve (AUC) and Akaike's information criterion (AIC score). Models with larger AUC values have a better fit, while lower AIC scores indicate models with more support. Ultimately, we used AIC scores to determine the model with the most support to predict right whale density. To ensure extrapolation errors did not occur in our density predictions, we visually inspected histograms of the environmental data used for model fitting against the environmental data used to make predictions.

Variance was estimated using the methods outlined by Miller et al.[70]. Because we did not use predictor variables to model our detection function, we used the delta method to propagate the uncertainty in detectability into the GAMs. We then used a multivariate normal distribution to simulate ten samples using the GAM parameters (β) and covariance matrix. For each 8-day period we calculated the predicted abundance for each grid cell ten times (one abundance estimate per grid cell for each of the β samples). We then used the Welford method to summarize the seasonal average density and variance for each grid cell.

Trade-off analysis

Wind energy development simulation. To determine the trade-offs between the financial costs of mitigation measures and their conservation benefit, we developed a wind energy construction simulation. In the simulation, 10.3-m diameter monopile foundations and transition pieces are installed 1 NM apart across the wind energy areas (Fig. 1a). We assume monopile foundations would be constructed using an industry-standard piling technique. This method involves dropping a hammer onto the monopile foundations to drive them into the stable seabed.

Noise transmitted during pile-driving is expected to have the biggest impact on cetaceans that communicate with low frequency sounds when compared with other potential wind energy construction impacts[71]. Pile-driving sound transmission is dependent on several factors including seasonal variation in oceanographic conditions, bathymetry, substrate, pile material and diameter and hammer energy[72]. The MMPA defines Level A harassment as any act of pursuit, torment or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild[44]. Level B harassment is defined as any act of pursuit, torment or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing a disruption of behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding or shelter. Acoustic exposure thresholds for Level A and B harassment are defined for protected species, and are used to quantify the size of the area surrounding the pile-driving that would encompass Level A and B take zones. Animals found within these zones would be exposed to acoustic thresholds that equate to a Level A or B take. Exposure to sound levels exceeding these thresholds within the zone result in a 'take' of the protected species. The allowable number of takes is defined in project permits.

To quantify the impact of wind energy development on right whales, we used predictions from our density surface model to calculate the number of whales that would occur within Level A and B take zones, where whales could be exposed to sound levels associated with Level A and B takes (hereafter, referred to as the predicted number of whales exposed to sound levels associated with Level A and B takes). We selected right whale density predictions from the 8-day period corresponding to the installation of the five selected turbines (see below for details on turbine selection). To propagate variation in the density estimates through the trade-off analysis we calculated the predicted number of whales exposed to sound levels associated with Level A and B takes ten times (that is, one for each of the ten density estimates we calculated per grid cell per 8-day period). Density predictions may be missing for a grid cell if environmental data were missing for that 8-day period. We replaced these missing values with the average density prediction for that grid cell from the previous and post 8-day period. If the previous and post 8-day period also had missing values, the density prediction was replaced with the monthly average for that grid cell. If the monthly average was also missing, the density was replaced with the seasonal average for that grid cell. We calculated the mean and variance of the ten density estimates to quantify the predicted number of whales exposed to Level A and B takes. We summed the predicted number of whales exposed to Level A and B takes over the development period to determine the predicted number of whales exposed to takes in each campaign.

The radial distance of Level A and B take ranges can be reduced using noise mitigation systems such as big bubble curtains. Compressed air is forced through holes in a hose, lying in a circle on the seafloor around the pile-driving event, emitting a bubble curtain into the water column. A double big bubble curtain consists of two hoses lying on the seafloor. The noise attenuation, and therefore the radial distances of the take ranges, for big bubble curtains can vary depending on the volume of compressed air, the size and spacing of the holes in the hose, the distance from the hose to the pile-driving location, current direction and speed and water depth[73]. Big bubble curtains have been optimized for up to 15 dB of noise attenuation and double big bubble curtains have been optimized for up to 18 dB of noise attenuation[74]. In our simulation, we conservatively assume a big bubble curtain attenuates noise up to 10 dB and a double big bubble curtain would attenuate noise up to 12 dB. To determine the radial distances of Level A and B take ranges we compiled data from the literature[45,46,55,75–77]. We found large variation in reported radial distances of Level A and B take ranges, dependent on the area, season and underwater noise and exposure modelling versus sound field verification estimates (Level A, 10 dB mean = 3.53 km, s.d. = 1.81; Level A, 12 dB mean = 3.98 km, s.d. = 2.00; Level B, 10 dB mean = 4.48 km, s.d. = 1.99; Level B, 12 dB mean = 3.77 km, s.d. = 0.81). Therefore, we decided to restrict our analysis to data from underwater noise and exposure modelling for the wind energy areas during the summer months as current permits require most construction to occur during this time[45–47]. We used the compiled data to calculate the median radial distance for Level A and B take ranges assuming 10 dB and 12 dB of noise attenuation (Table 1). However, to incorporate the wide variation in radial distances associated with Level A and B take thresholds, we conducted our trade-off analysis using the median radial distance, as well as the median radial distance +20% and the median radial distance −20%. This variation in radial distance allowed us to estimate the predicted number of right whales exposed to Level A and B take noise thresholds when radial distances were estimated conservatively (median −20%), as well as generously (median +20%).

Monopile locations were spaced 1 NM apart, throughout the prediction box, and then clipped to the wind energy areas (Fig. 1a). We ran ten simulations, representing ten development campaigns. To determine the spatial location of each campaign, we randomly chose one monopile location in the wind energy area. Each simulated campaign covered a circular area of approximately 468 km^2, comparable to proposed projects in the wind energy area[77]. The circular buffer was placed around the randomly chosen monopile location (Fig. 1c). We assumed that a hypothetical wind energy developer would plan to drive 70 monopiles within the circular buffer; in the wind energy area, the number of turbines per wind farm range from 62 to 130 (refs. 75,76,78). For each 8-day period throughout the year, we randomly chose five of the 70 turbines from within the circular buffer that had adequate weather for pile-driving one turbine in one day. We assumed 2 h were required to drive a monopile. Weather was considered adequate for pile-driving when the mean wind speed was at or below 15 m s^{-1} at 100 m above mean sea level for 2 h and visibility was greater than 2 km (Supplementary Table 1). Pile-driving could only occur during daylight hours, which varied monthly (Supplementary Table 1). Wind conditions were derived from the hourly Copernicus Era5 re-analysis dataset. The 100-m u-component and the 100-m v-component of wind were downloaded and combined ($w_s = \text{sqrt}(u^2 + v^2)$) to estimate average hourly wind speed for 2018 in the wind energy area. To determine days with visibility conditions adequate for pile-driving, monthly visibility conditions were evaluated using the International Comprehensive Ocean–Atmosphere Data Set database[79]. For each month, we calculated the percentage of days that were subject to visibility less than 2 km using local ship-based observations collected between 2013 and 2024. We then took the monthly average of these percentages and randomly assigned the corresponding proportion of low visibility days to our dataset (Supplementary Table 1).

Wind energy development mitigation scenarios. Within our wind energy development simulation, we consider ten mitigation scenarios (Table 1 and Supplementary Table 1). The no seasonal mitigation scenario assumes pile-driving can occur throughout the year and requires 10 dB of noise attenuation via a big bubble curtain. The no seasonal mitigation and additional noise attenuation scenario assumes pile-driving can occur throughout the year and requires an additional noise attenuation device (a double big bubble curtain) that results in 12 dB of noise attenuation.

The seasonal restriction scenarios maintain the single big bubble curtain (10 dB noise attenuation), but further limit the months when pile-driving can occur (Table 1 and Supplementary Table 1). The current schedule seasonal restriction scenario assumes piling cannot occur from 1 January through 30 April[83]. In the June–December seasonal restriction scenario, pile-driving occurs from 1 June through

31 December. In the May–November seasonal restriction scenario, pile-driving occurs from 1 May through 30 November. Finally, in the June–November seasonal restriction scenario, pile-driving occurs from 1 June through 30 November. Scenarios labelled with 'additional noise attenuation' use the piling schedule defined previously and require an additional noise attenuation device (a double big bubble curtain), resulting in 12 dB of noise attenuation.

Cost analysis. We assume a daily cost rate of US$805,000 in 2018. This includes a heavy-lift vessel (US$765,000), project resources (US$20,000) and two guard vessels (US$10,000 each). These costs were based on the literature[32–34] and adjusted for inflation. We also estimate a yearly cost of mobilization (US$30 million)[35]. To determine the cost of each scenario we multiply the campaign duration by the daily cost rate and add the yearly mobilization cost. Because heavy-lift vessels are limited worldwide, we assume that one pile would be driven at a time. Therefore, each campaign would require one double big bubble curtain at an additional cost of US$7 million[28].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

North Atlantic right whale sightings data were obtained from the North Atlantic Right Whale Consortium. Access to these data is subject to the data use policies and approval procedures of the Consortium. Researchers may request access to the data through the Consortium data request process at https://www.narwc.org/accessing-narwc-data.html. The depth data from the Northeast Coastal Relief Model can be accessed in the marmap package in R. The Aqua MODIS Global Mapped Chlorophyll data sampled at 8-day intervals at a 4-km spatial resolution can be accessed at https://oceancolor.gsfc.nasa.gov The 4-day salinity data on a 1/4° grid from the Multi-Mission Optimally Interpolated Sea Surface Salinity Global Dataset v.1 can be accessed at https://www.earthdata.nasa.gov/data/catalog/pocloud-oisss-l4-multimission-7day-v1-1.0. Daily SST data on a 0.01° grid can be obtained from the GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis (v.4.1) at https://doi.org/10.5067/GHGMR-4FJ04 (ref. 69).

Code availability

All code used for data processing, statistical analyses and figure generation is available via GitHub at https://github.com/lganley/tradeoffs. The specific version of the code supporting the findings of this study is available via Zenodo at https://doi.org/10.5281/zenodo.20510084 (ref. 80).

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Author contributions

L.C.G., J.V.R., D.E.P. and A.N.R. conceived the study. L.C.G. designed the analysis in close consultation with J.V.R., A.N.R., I.S. and C.C. L.C.G. performed the analysis with help from M.R. O.O. coordinated, led and participated in the collection of datasets that were integral to the analysis. L.C.G. wrote the first draft with initial contributions from M.R. All authors contributed to reviewing and improving the paper.

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Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-026-02696-9.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-026-02696-9.

Correspondence and requests for materials should be addressed to Laura C. Ganley.

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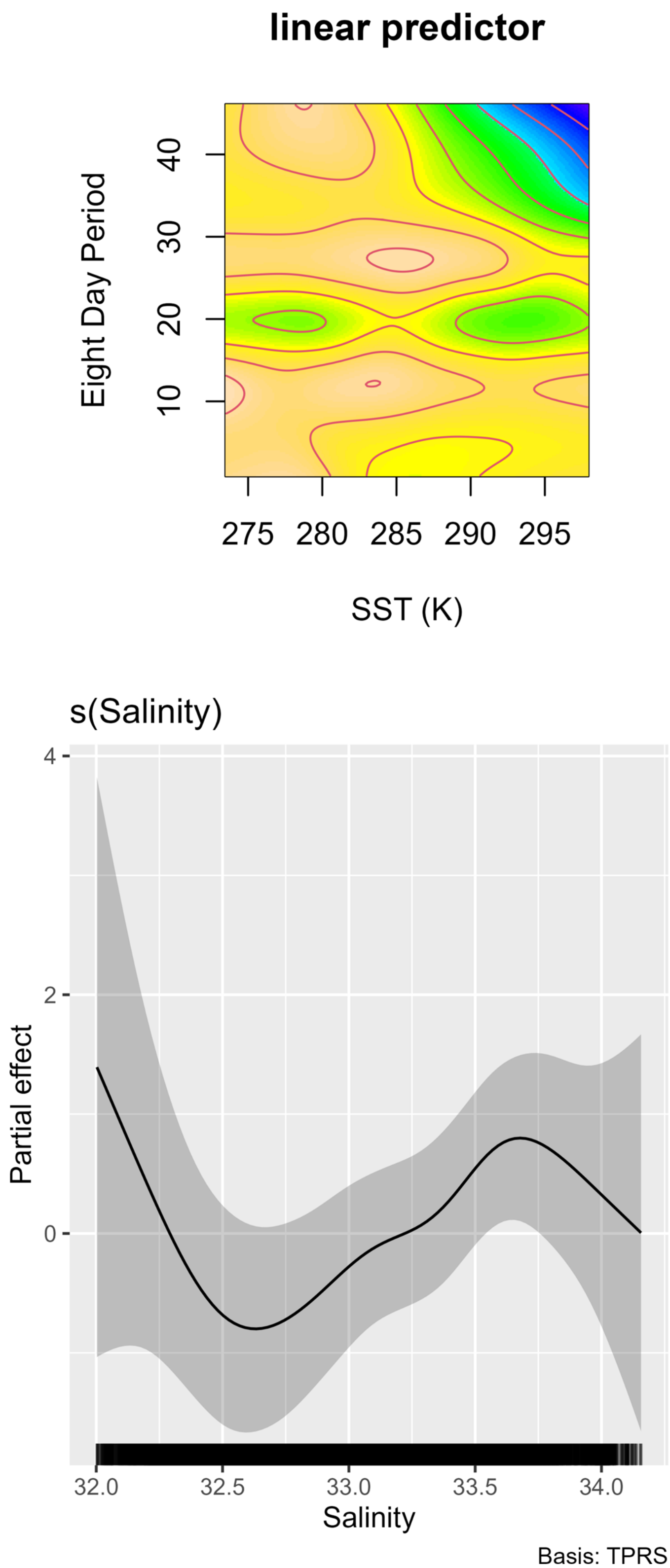
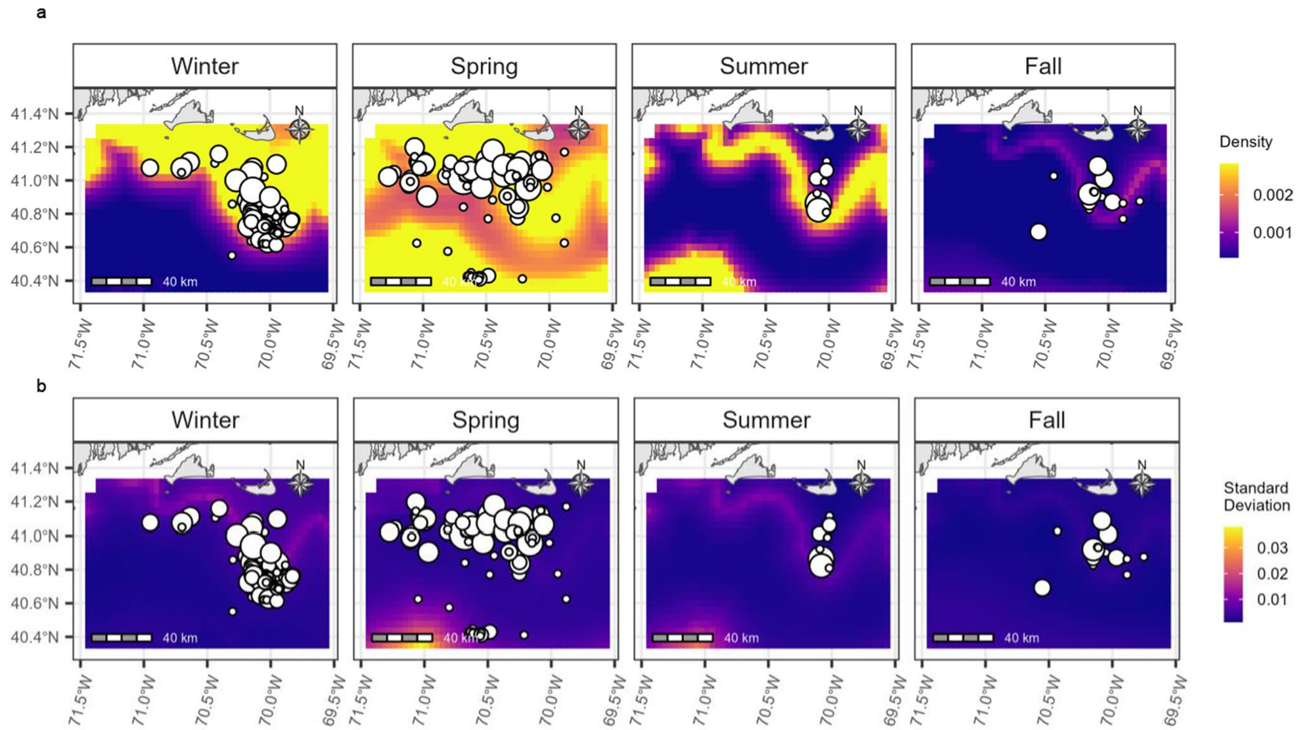


Extended Data Fig. 1 | Visualizations of fitted values from the density surface model with the most support for the relationship between right whale density and environmental covariates. The relationship between right whale density and the interaction between time of year (eight-day period) and sea surface temperature (SST) and distance to the 30 m isobath. Partial effects of salinity on right whale density according to the model with the most support. The gray shading represents 95% confidence intervals for the mean effect.



Extended Data Fig. 2 | Seasonally averaged right whale density predictions and standard deviations from the density surface model fit with aerial survey data collected between 2011 and 2020. The density surface model was fit using n = 14,410 survey segments derived from 137 aerial surveys. Survey segments, the unit of analysis, were chopped according to the Supplemental segment chopping methods, with 89% of the segments meeting the target length of 4.6 km. Density (**a**) and standard deviation (**b**) ranges were selected to encompass all values within the 25 and 75% quantiles. White dots show right whale sighting locations from the aerial surveys. US geographic boundaries from the US States (Generalized) layer within the Esri Data & Maps suite (https://www.arcgis.com/home/item.html?id=c66cec727b7b4ef99e470e50b9c98663, 2004), Esri, TomTom, USGS, FAO, NOAA, NRCan.

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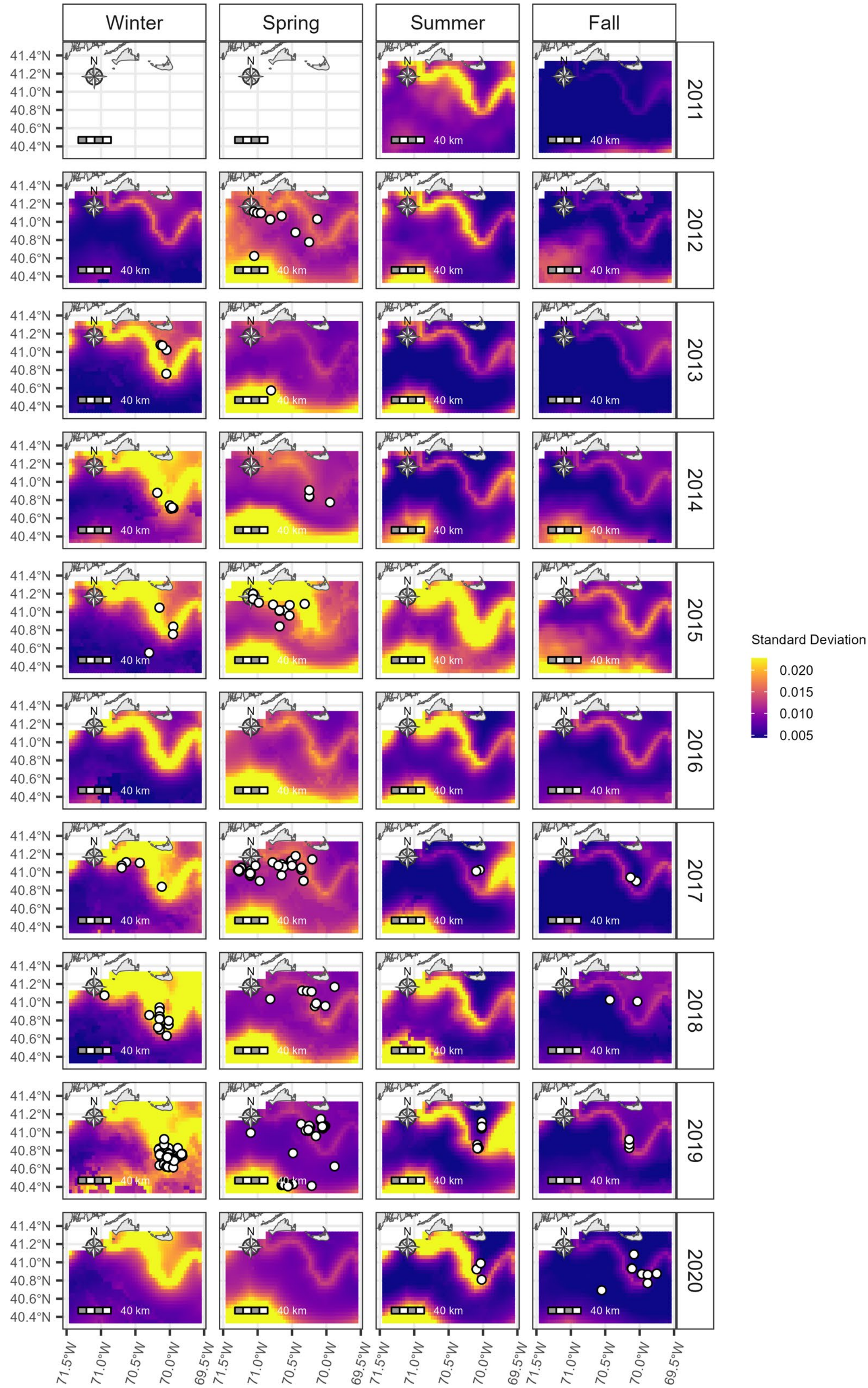
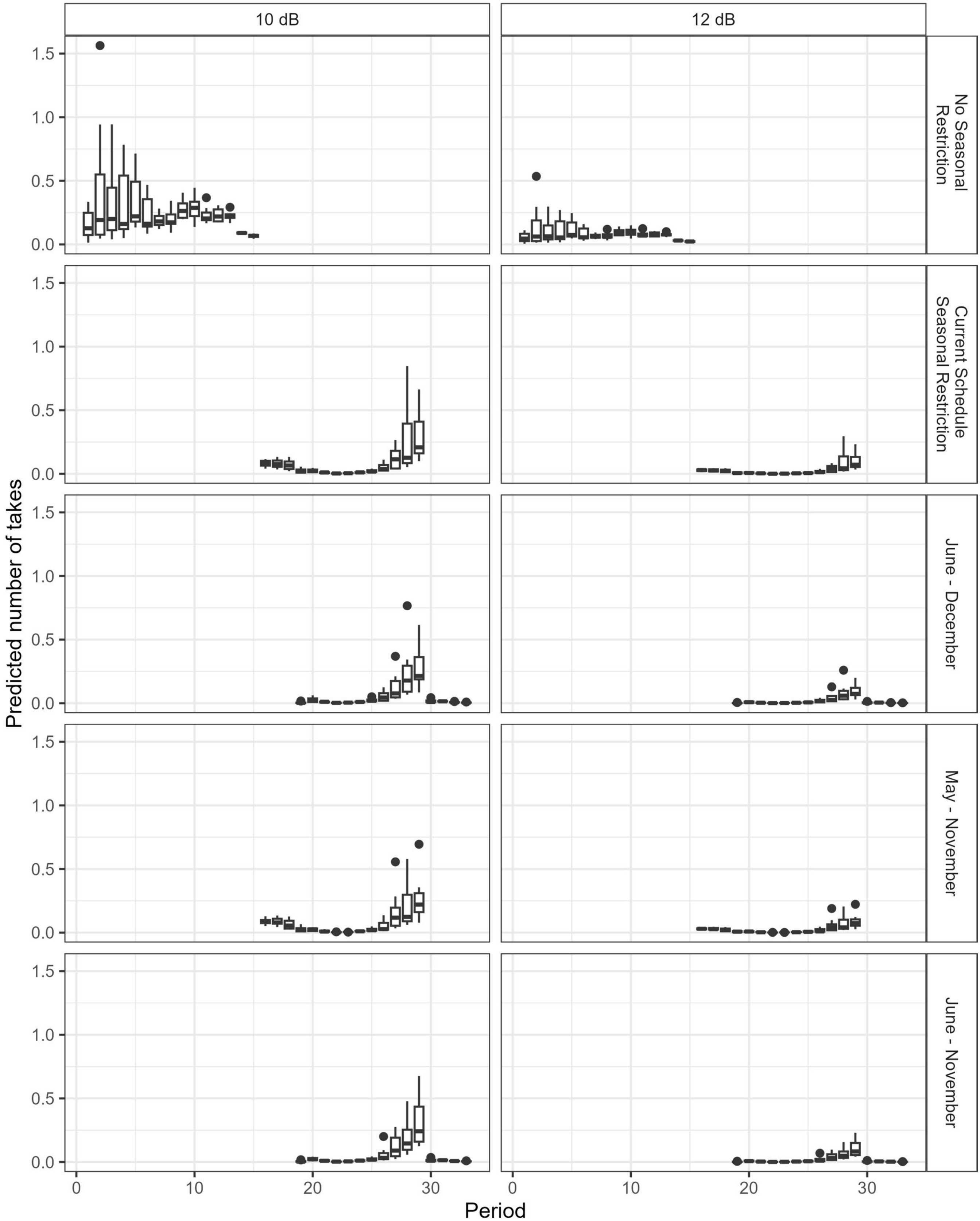


Extended Data Fig. 3 | Seasonally averaged right whale standard deviation of density predictions for each year from the density surface model fit with aerial survey data collected between 2011 and 2020. The density surface model was fit using n = 14,410 survey segments derived from 137 aerial surveys. Survey segments, the unit of analysis, were chopped according to the Supplemental segment chopping methods, with 89% of the segments meeting the target length of 4.6 km. Standard deviation ranges were selected to encompass all values within the 25 and 75% quantiles. White dots show right whale sighting locations from the aerial surveys. US geographic boundaries from the US States (Generalized) layer within the Esri Data & Maps suite (https://www.arcgis.com/home/item.html?id=c66cec727b7b4ef99e470e50b9c98663, 2004), Esri, TomTom, USGS, FAO, NOAA, NRCan.



Extended Data Fig. 4 | The predicted number of level A takes a campaign would use in each eight day period using the lower threshold radial distances. The mitigation measures in the left panel include 10 dB of noise attenuation, while the right panel include 12 dB of noise attenuation. The boxplots show median values and the lower and upper hinges correspond to the first and third quartiles. The upper (lower) whisker extends to the largest (smallest) value no further than 1.5x the inter-quartile range. Data beyond the end of the whiskers are outliers. Boxplots summarize values from n = 10 wind energy development campaigns per week. For each campaign, within each eight day period, a maximum of five wind turbines were driven when weather allowed, with each turbine measured ten times to incorporate the variation from the ten right whale density surface model simulations.

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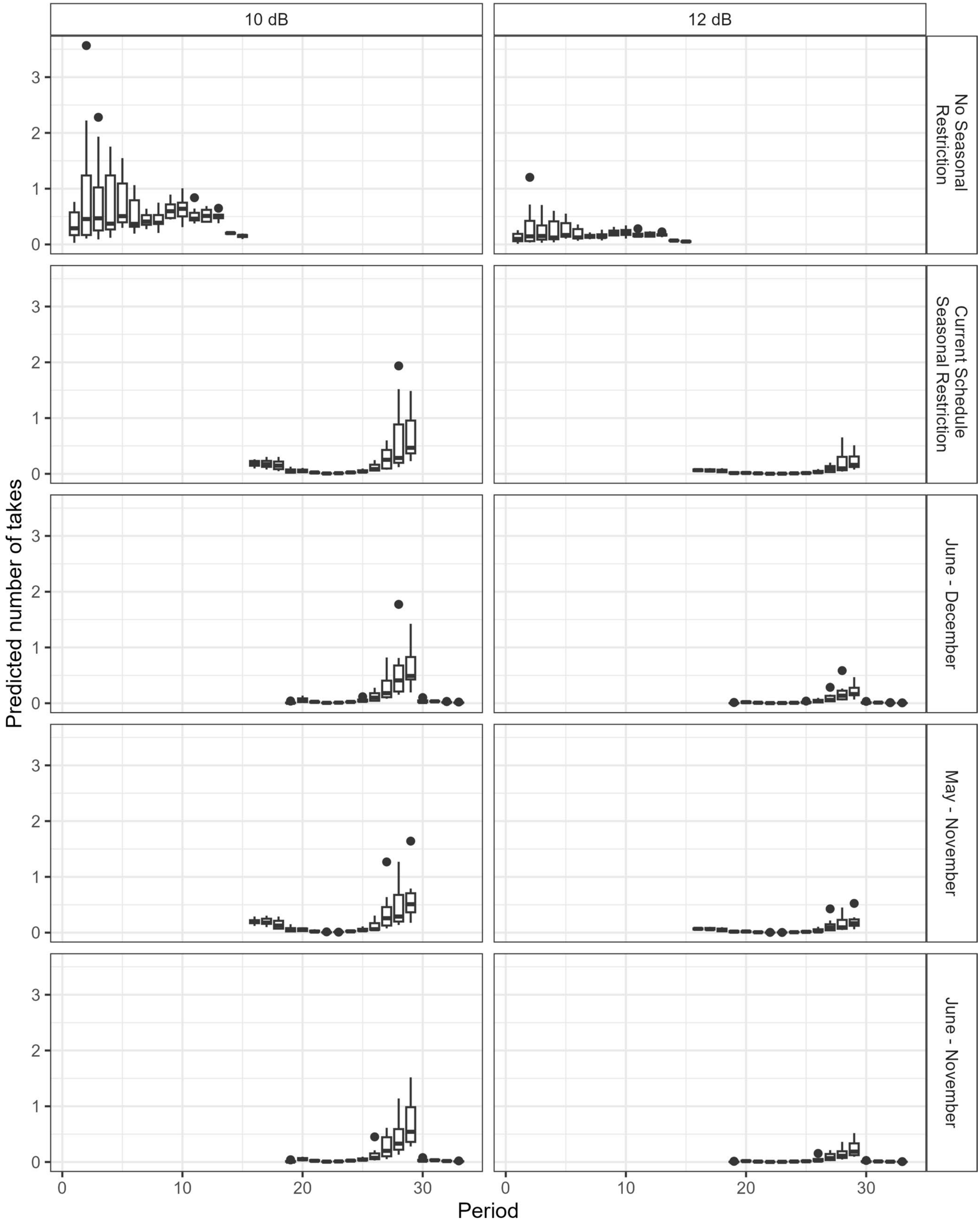

Extended Data Fig. 5 | The predicted number of level A takes a campaign would use in each eight day period using the upper threshold radial distances. The mitigation measures in the left panel include 10 dB of noise attenuation, while the right panel include 12 dB of noise attenuation. The boxplots show median values and the lower and upper hinges correspond to the first and third quartiles. The upper (lower) whisker extends to the largest (smallest) value no further than 1.5x the inter-quartile range. Data beyond the end of the whiskers are outliers. Boxplots summarize values from n = 10 wind energy development campaigns per week. For each campaign, within each eight day period, a maximum of five wind turbines were driven when weather allowed, with each turbine measured ten times to incorporate the variation from the ten right whale density surface model simulations.

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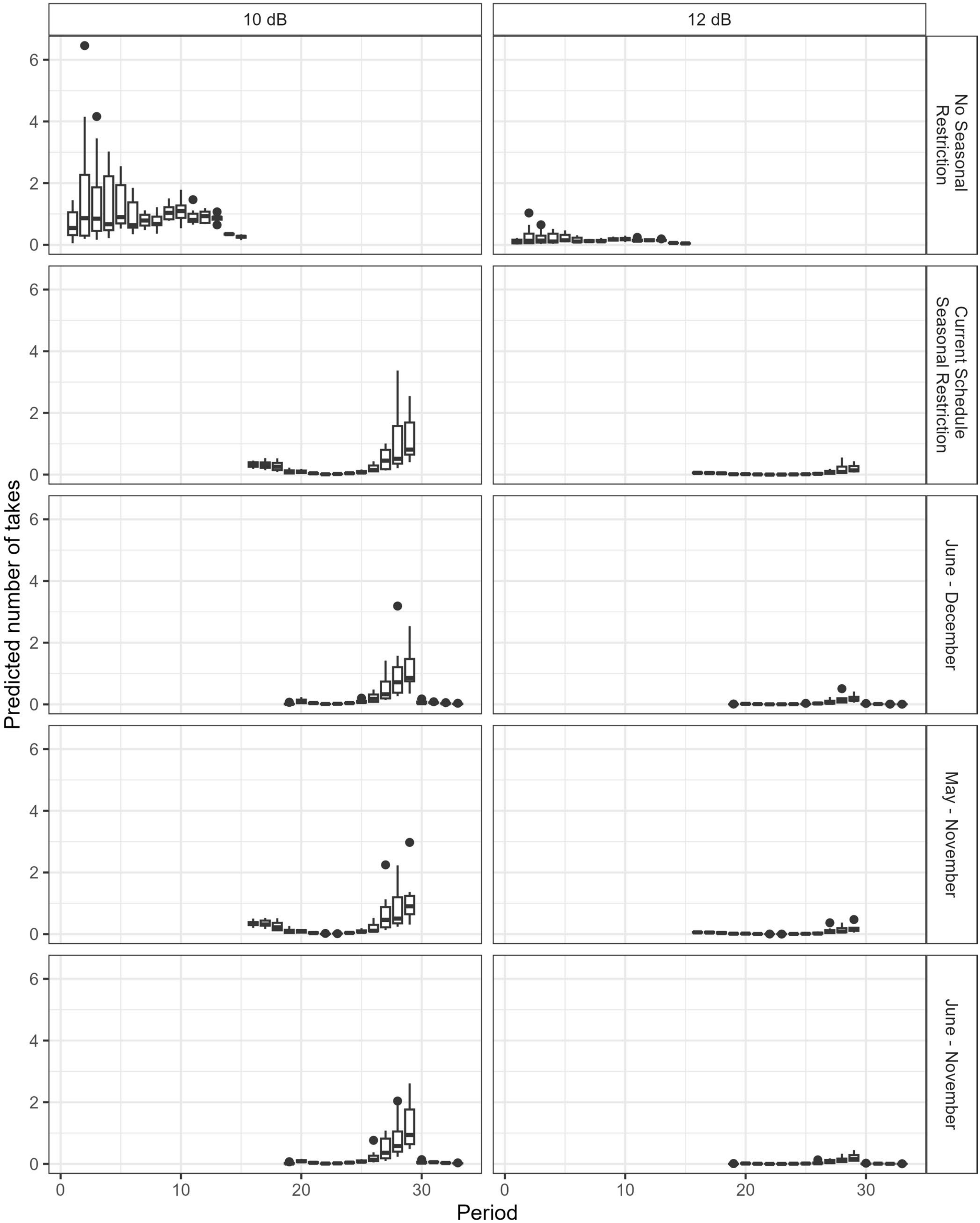

Extended Data Fig. 6 | The predicted number of level B takes a campaign would use in each eight day period using the lower threshold radial distances. The mitigation measures in the left panel include 10 dB of noise attenuation, while the right panel include 12 dB of noise attenuation. The boxplots show median values and the lower and upper hinges correspond to the first and third quartiles. The upper (lower) whisker extends to the largest (smallest) value no further than 1.5x the inter-quartile range. Data beyond the end of the whiskers are outliers. Boxplots summarize values from n = 10 wind energy development campaigns per week. For each campaign, within each eight day period, a maximum of five wind turbines were driven when weather allowed, with each turbine measured ten times to incorporate the variation from the ten right whale density surface model simulations.

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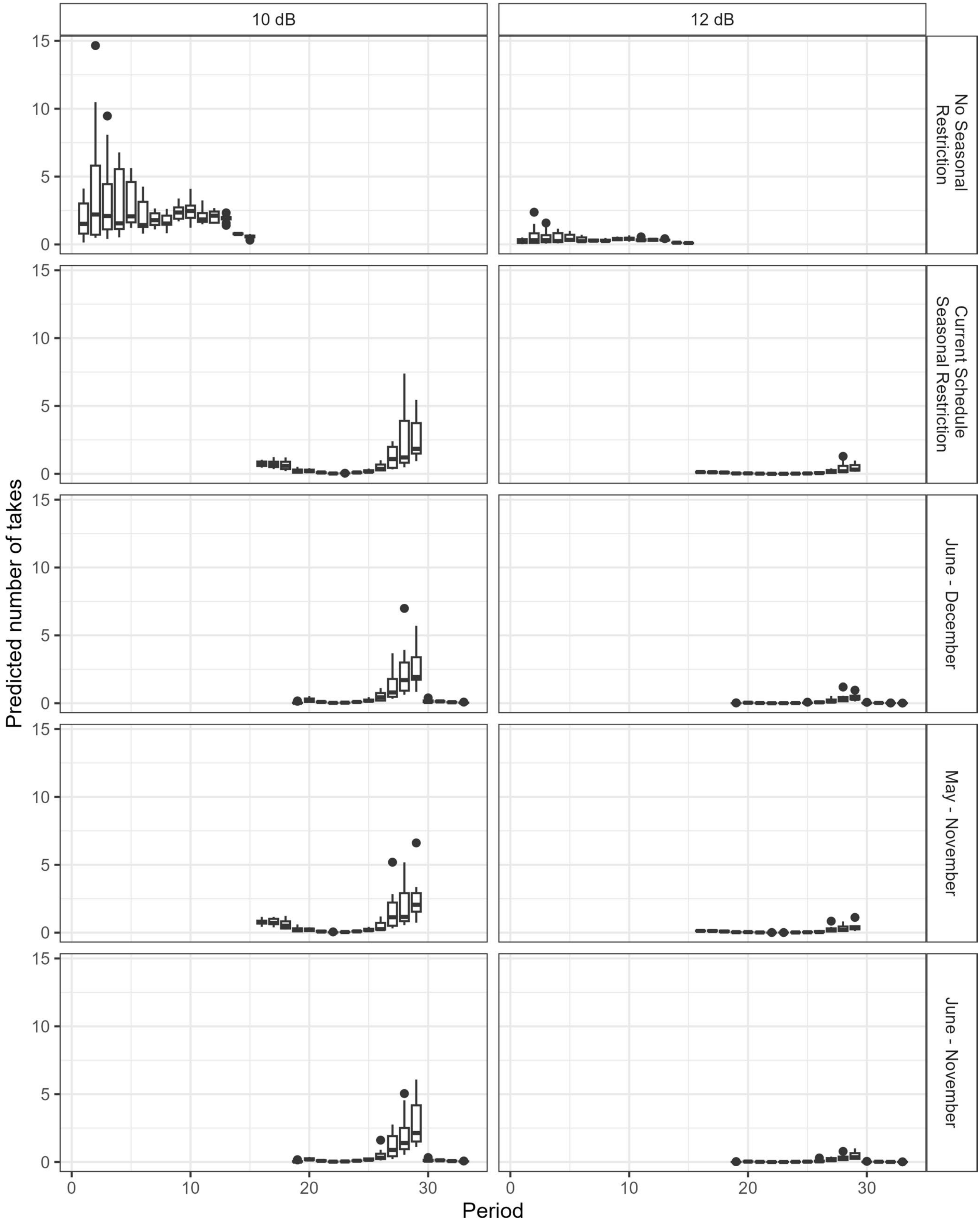

Extended Data Fig. 7 | The predicted number of level B takes a campaign would use in each eight day period using the upper threshold radial distances. The mitigation measures in the left panel include 10 dB of noise attenuation, while the right panel include 12 dB of noise attenuation. The boxplots show median values and the lower and upper hinges correspond to the first and third quartiles. The upper (lower) whisker extends to the largest (smallest) value no further than 1.5x the inter-quartile range. Data beyond the end of the whiskers are outliers. Boxplots summarize values from n = 10 wind energy development campaigns per week. For each campaign, within each eight day period, a maximum of five wind turbines were driven when weather allowed, with each turbine measured ten times to incorporate the variation from the ten right whale density surface model simulations.

https://doi.org/10.1038/s41558-026-02696-9

Extended Data Table 1 | Density surface models were used to relate aerial survey data, collected between 2011 and 2020, to oceanographic variables and make right whale density predictions

Model	AIC	AUC	RMSE	TSS
Distance to 30m isobath*period, period* Sea Surface Temperature, Salinity	1,965	0.89	0.551	0.68
Distance to 40m isobath*period, period*Sea Surface Temperature, Salinity	1,967	0.89	0.549	0.67
Depth, Period*Sea Surface Temperature, Salinity	1,973	0.88	0.554	0.66
Distance to 30m isobath with depth*period, Sea Surface Temperature*period, Salinity	1,976	0.87	0.551	0.62
Distance to 30m isobath with depth, period*Sea Surface Temperature, Salinity	2,022	0.83	0.554	0.54
Distance to 40m isobath, Sea Surface Temperature, Salinity, Chlorophyll	2,037	0.81	0.554	0.53
Distance to 40m isobath, Sea Surface Temperature	2,039	0.80	0.554	0.51
Sea Surface Temperature, Salinity, Chlorophyll	2,047	0.78	0.555	0.48
Sea Surface Temperature	2,051	0.76	0.555	0.46
Distance to 40m isobath	2,111	0.66	0.556	0.27

The model with the lowest Akaike Information Criterion (AIC) score was chosen as the model with the most relative support. We used Area Under the Receiver Curve (AUC), root mean squared error (RMSE), and total sum of squares (TSS) as tests of goodness-of-fit. Models with RMSE values between 0 and 1 are considered to fit sufficiently.

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Corresponding author(s): Laura Ganley

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used to collect the data in this study.
Data analysis	We used the R programming language and R Studio to write code for this study. All of the code is available in my public github repository https://github.com/lganley/tradeoffs, which is also linked in my code availability statement.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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- A description of any restrictions on data availability
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North Atlantic right whale sightings data were obtained from the North Atlantic Right Whale Consortium. Access to these data is subject to the Consortium's data use policies and approval procedures. Researchers may request access to the data through the Consortium data request process at https://www.narwc.org/accessing-narwc-data.html. The depth data from the Northeast Coastal Relief Model can be accessed in the marmap package in R. The Aqua MODIS Global Mapped

Chlorophyll data sampled at eight-day intervals at a 4 km spatial resolution can be accessed at https://oceancolor.gsfc.nasa.gov/ The four-day salinity data on a 1/4° grid from the Multi-Mission Optimally Interpolated Sea Surface Salinity Global Dataset V1 can be accessed at https://www.earthdata.nasa.gov/data/catalog/pocloud-oisss-l4-multimission-7day-v1-1.0. Daily sea surface temperature data on a 0.01 ° grid can be obtained from the GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis (v4.1) at https://doi.org/10.5067/GHGMR-4FJ04.

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Population characteristics	*Describe the covariate-relevant population characteristics of the human research participants (e.g. age, genotypic information, past and current diagnosis and treatment categories). If you filled out the behavioural & social sciences study design questions and have nothing to add here, write "See above."*
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Ethics oversight	*Identify the organization(s) that approved the study protocol.*

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Ecological, evolutionary & environmental sciences study design

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Study description	We used a density surface model (Extended Data Table 1) fit with aerial survey data (Fig. 1b) to estimate the number of right whales exposed to sound levels associated with Level A and B takes during pile-driving activities under 10 mitigation scenarios (Tables 1 & Supplementary Table 1). Mitigation scenarios included combinations of Seasonal Restrictions and Additional Noise Attenuation Systems and were compared to the Current Schedule Seasonal Restriction scenario (hereafter "% change in takes"). We used the literature to estimate the median, median +20%, and median -20% radial distance that pile-driving noise would travel 45–47. The cost of each campaign depends on the number of days required to drive 70 monopiles, which can vary due to weather conditions. We estimated the cost of each campaign assuming a daily rate of $805,000 in 201832–34. This cost includes a Heavy Lift Vessel ($765,000), project resources ($20,000), and two guard vessels ($10,000 each). We also include a yearly cost of mobilization ($30M)35. We apply an additional cost of $7M for a Double Big Bubble Curtain28.
Research sample	We used sightings of 600 North Atlantic right whales collected by aerial surveys between 2011 and 2020. This sample is meant to represent the animals that may be exposed to wind energy development in the Massachusetts Rhode Island Wind Energy Areas (specifically) or more broadly protected species that may be impacted by renewable energy development.
Sampling strategy	Our study does not have technical replicates (repeated measures of the same unit). We used aerial survey transects conducted across separate sampling occasions. Each 4.6 km survey segment constituted the unit of replication.
Data collection	Whale sightings were collected during aerial surveys, flown approximately twice monthly, in Southern New England between 2011 and 2020 (Fig. 1b). Aerial surveys were flown at a ground speed of 185 km/h and an altitude of 305 m, in a Cessna Skymaster 337 O-2A aircraft. Trackline effort and environmental conditions were recorded every 2-5 seconds. Two observers, one on either side of the aircraft, scanned their field of view for whales. Sightings were recorded when they were perpendicular to the aircraft. Marks on

the wing struts were used to record the estimated distance of the sighting from the trackline. When right whales were sighted, the plane diverted from the trackline to obtain photo-identification data for monitoring use of the area by individual whales.

Timing and spatial scale

Data were collected between 2011 and 2020, approximately twice monthly. Surveys began in 2011, 2020 was chosen as the end date because the survey plane and altitude changed due to the installation of turbines. We are now beginning to account for these changes, but at the time of this analysis those changes had not yet been addressed. Survey tracklines are spaced approximately six nm apart, but shift approximately 1/2 nm in either direction depending on a random generator that is drawn from at the beginning of each survey to randomize the start point.

Data exclusions

No data were excluded.

Reproducibility

We compared our density surface model results with those of Roberts et al., 2016 and 2022 and found that they were generally similar. In addition, our survey design is reproducible in that we conducted repeated aerial surveys using standardized survey protocols and transect designs. We wrote custom code that is publicly available for data processing, fitting the detection functions, and density surface modeling. We used several goodness of fit checks (AUC, RMSE, TSS, and AIC) for diagnostic assessments.

Randomization

Our ecology survey did not have a control group because we were attempting to estimate animal density and how it varied spatially across the southern New England region rather than looking at the experimental variation in density based on treatments.

Blinding

Blinding was not relevant to the density surface model using aerial survey data because there were no treatments, the surveys followed predefined transects that shifted based on a random number generator, detections are recorded in real time, and modeling is computational minimizing opportunities for biases.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions

Whale sightings were collected during aerial surveys, flown approximately twice monthly, in Southern New England between 2011 and 2020 (Fig. 1b). Aerial surveys were flown at a ground speed of 185 km/h and an altitude of 305 m, in a Cessna Skymaster 337 O-2A aircraft. Trackline effort and environmental conditions were recorded every 2-5 seconds. Two observers, one on either side of the aircraft, scanned their field of view for whales. Sightings were recorded when they were perpendicular to the aircraft. Marks on the wing struts were used to record the estimated distance of the sighting from the trackline. When right whales were sighted, the plane diverted from the trackline to obtain photo-identification data for monitoring use of the area by individual whales.

Location

This study was conducted in the Massachusetts/Rhode Island Wind Energy Areas in Southern New England. Surveys were conducted at 305 m altitude.

Access & import/export

We collected data on North Atlantic right whales using NOAA/NMFS permit #'s 14233 and #19674

Disturbance

No disturbances were caused by this study.

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Wild animals	North Atlantic right whales of all demographic classes were observed in the field. No animals were captured or killed for this study.
Reporting on sex	*Indicate if findings apply to only one sex; describe whether sex was considered in study design, methods used for assigning sex. Provide data disaggregated for sex where this information has been collected in the source data as appropriate; provide overall numbers in this Reporting Summary. Please state if this information has not been collected. Report sex-based analyses where performed, justify reasons for lack of sex-based analysis.*
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Flow Cytometry

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☐ All plots are contour plots with outliers or pseudocolor plots.

☐ A numerical value for number of cells or percentage (with statistics) is provided.

Methodology

Sample preparation	*Describe the sample preparation, detailing the biological source of the cells and any tissue processing steps used.*
Instrument	*Identify the instrument used for data collection, specifying make and model number.*
Software	*Describe the software used to collect and analyze the flow cytometry data. For custom code that has been deposited into a community repository, provide accession details.*
Cell population abundance	*Describe the abundance of the relevant cell populations within post-sort fractions, providing details on the purity of the samples and how it was determined.*
Gating strategy	*Describe the gating strategy used for all relevant experiments, specifying the preliminary FSC/SSC gates of the starting cell population, indicating where boundaries between "positive" and "negative" staining cell populations are defined.*

☐ Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

Magnetic resonance imaging

Experimental design

Design type	*Indicate task or resting state; event-related or block design.*
Design specifications	*Specify the number of blocks, trials or experimental units per session and/or subject, and specify the length of each trial or block (if trials are blocked) and interval between trials.*
Behavioral performance measures	*State number and/or type of variables recorded (e.g. correct button press, response time) and what statistics were used to establish that the subjects were performing the task as expected (e.g. mean, range, and/or standard deviation across subjects).*

Acquisition

Imaging type(s) | *Specify: functional, structural, diffusion, perfusion.*

Field strength | *Specify in Tesla*

Sequence & imaging parameters | *Specify the pulse sequence type (gradient echo, spin echo, etc.), imaging type (EPI, spiral, etc.), field of view, matrix size, slice thickness, orientation and TE/TR/flip angle.*

Area of acquisition | *State whether a whole brain scan was used OR define the area of acquisition, describing how the region was determined.*

Diffusion MRI ☐ Used ☐ Not used

Preprocessing

Preprocessing software | *Provide detail on software version and revision number and on specific parameters (model/functions, brain extraction, segmentation, smoothing kernel size, etc.).*

Normalization | *If data were normalized/standardized, describe the approach(es): specify linear or non-linear and define image types used for transformation OR indicate that data were not normalized and explain rationale for lack of normalization.*

Normalization template | *Describe the template used for normalization/transformation, specifying subject space or group standardized space (e.g. original Talairach, MNI305, ICBM152) OR indicate that the data were not normalized.*

Noise and artifact removal | *Describe your procedure(s) for artifact and structured noise removal, specifying motion parameters, tissue signals and physiological signals (heart rate, respiration).*

Volume censoring | *Define your software and/or method and criteria for volume censoring, and state the extent of such censoring.*

Statistical modeling & inference

Model type and settings | *Specify type (mass univariate, multivariate, RSA, predictive, etc.) and describe essential details of the model at the first and second levels (e.g. fixed, random or mixed effects; drift or auto-correlation).*

Effect(s) tested | *Define precise effect in terms of the task or stimulus conditions instead of psychological concepts and indicate whether ANOVA or factorial designs were used.*

Specify type of analysis: ☐ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference | *Specify voxel-wise or cluster-wise and report all relevant parameters for cluster-wise methods.*

(See Eklund et al. 2016)

Correction | *Describe the type of correction and how it is obtained for multiple comparisons (e.g. FWE, FDR, permutation or Monte Carlo).*

Models & analysis

n/a	Involved in the study
☐	☐ Functional and/or effective connectivity
☐	☐ Graph analysis
☐	☒ Multivariate modeling or predictive analysis

Functional and/or effective connectivity | *Report the measures of dependence used and the model details (e.g. Pearson correlation, partial correlation, mutual information).*

Graph analysis | *Report the dependent variable and connectivity measure, specifying weighted graph or binarized graph, subject- or group-level, and the global and/or node summaries used (e.g. clustering coefficient, efficiency, etc.).*

Multivariate modeling and predictive analysis | *Specify independent variables, features extraction and dimension reduction, model, training and evaluation metrics.*