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Spatial planning offshore wind energy farms in California for mediating fisheries and wildlife conservation impacts

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ABSTRACT

Achieving a blue economy will require reconciling the value of emerging ocean uses with their impacts on the seascape and sectors with historical access to marine resources and areas. To meet this challenge, we developed an analytical framework for conducting marine spatial planning through tradeoff analysis, and applied it to prospective offshore wind energy development in the ~974 km^2 Morro Bay, California, USA Wind Energy Area (WEA). We generated spatial data layers estimating MW power production and impacts on fisheries value and marine wildlife conservation (seabird and cetacean populations) from wind farm development. We then quantified each sector's response to plans of development across the WEA and inside three leases recently acquired by the energy industry for prospective development. Finally, we integrated the sector response data into an analytical framework for mitigating sector tradeoffs with novel spatial planning solutions (maps of wind farm size, location, and configuration) that optimally maximize value to the emergent energy sector (MW power) while minimizing impacts to historical (fisheries and wildlife) sectors. We found that western sites in the WEA had the highest potential power production concurrent with the lowest impact on the historical sectors, revealing the eastern lease to be less efficient at optimally balancing the sector's objectives relative to the development of the central or western leases or the optimal spatial plans identified in the tradeoff analysis. Within a lease, tradeoff analysis found spatial planning able to generate out-sized savings in fisheries value with only modest losses in MW power – for example, by avoiding development in just 5% of the eastern lease to preserve nearly half its fisheries value and still generate 95% its total power potential. Small-scale development opportunities (e.g., a pilot project) with significant power potential and no fisheries impact were also identified, in this case by placing turbines in an area in the western lease with no fisheries value and high power production potential. These plans would also have a relatively low impact on the wildlife conservation sectors, due to decreases in vulnerability levels of both seabird and cetacean populations to turbines going from east to west across the WEA. Our results can inform site evaluation and permitting processes for wind energy development in the Morro Bay WEA. We also expect the tradeoff analysis framework we

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developed to provide a simple and actionable analytical tool for supporting marine spatial planning of offshore wind energy and other emerging blue economy activities from a balanced perspective that values emerging uses of marine resources alongside existing socio-economic and conservation interests.

1. Introduction

California has an ambitious plan to develop renewable energy (CARB 2018), and the Central Coast is being pursued by industry and evaluated by permitting agencies for offshore wind energy development (BOEM 2018). This region is a potentially prime location for offshore wind energy because (i) it is outside National Marine Sanctuary boundaries (including the proposed Chumash National Marine Sanctuary; NOAA, 2024a); (ii) onshore power transmission infrastructure exists at the retired Dynegy Power Plant in Morro Bay, Diablo Canyon Nuclear Power Plant at Point Buchon (DCNPP), and Vandenberg Air Force Base near Purisima Point; (iii) federal waters include substantial areas inside of the 1300 m isobath, the projected limit for offshore floating wind turbines (Musial et al., 2016b; BOEM, 2022); and, (iv) it is located in a region of California with moderately strong wind fields (Musial et al., 2016b; Wang et al., 2019a). Consequently, the Bureau of Ocean Energy Management (BOEM), which issues leases for offshore energy facility development, the California Energy Commission (CEC), the State's energy policy and planning agency, and Federal and State policymakers all support gathering information that can be used to evaluate and inform permitting of offshore wind energy development along the Central Coast (White, 2016, CA-AB-525, 2021, TWH, 2023; DataBasin, 2024).

Starting in 2018 and finalized in 2022, BOEM delineated a ~974 km^2 Wind Energy Area (WEA) approximately 32 km off the Central Coast of California in depths ranging from 700 to 1300 m (Cooperman et al., 2022) (Fig. 1). In December of 2023, BOEM hosted its first ever offshore wind lease sale on the Pacific Coast, with three companies securing leases in the Morro Bay WEA for a total of $425.6 million (BOEM, 2023). The leases collectively cover the entire WEA and approximately divide its surface area evenly (Fig. 1). If fully built out, the WEA could contain more than 200 turbines able to generate nearly 2 GW in realized power (Wang et al., 2022a) – roughly equivalent to the realized power from DCNPP (EIA, 2022), which supplies nearly 10% of California's energy portfolio and is scheduled to be decommissioned in 2030 (PG&E, 2022).

The Central Coast is also host to a vibrant commercial fishery and biodiverse marine ecosystem providing many ecosystem service values that could be impacted by offshore wind energy development (Farr et al., 2021). Commercial fisheries landings in Morro Bay and Port San Luis are valued at around $10 million annually (CDFG 2018). Sablefish (black cod) and other important groundfish are caught in deeper waters (>300 m) that could overlap with offshore wind facilities, including the Morro Bay WEA (Wang et al., 2022b, Wang et al. 2024). Therefore, displacement of the fishery and lost revenue to the commercial fisheries sector are possible issues.

The Central Coast also supports an abundance of marine wildlife. The region is frequented by Endangered Species Act Threatened and Endangered whale species, which could face the danger of entanglement with wind energy turbine platforms and their mooring structures (Wilson et al., 2007; Maxwell et al., 2022). Given the physical characteristics of the mooring systems required for floating deepwater offshore wind energy turbines, it is unlikely that whales or other marine mammals would become directly entangled in the

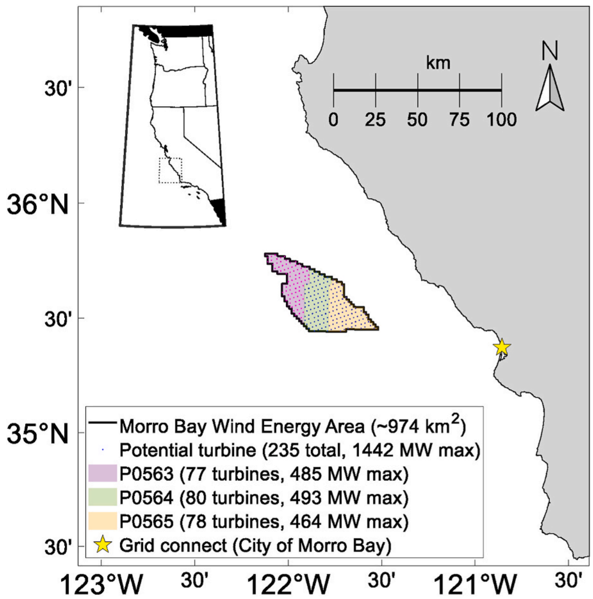

Fig. 1. California central coast study region, Morro Bay Wind Energy Area (WEA), and three wind energy lease areas that are the focus of the tradeoff analysis. Each of the 235 total grid cells with 2 km by 2 km spacing in the WEA were considered for wind energy turbine development.

moorings themselves. However, there is concern for secondary entanglement, which involves an organism becoming entangled in derelict fishing gear that has accumulated on a facility component, and tertiary entanglement, in which an organism already entangled in gear swims through a facility and the gear becomes entangled with a facility component (Farr et al., 2021; Maxwell et al., 2022). Any such entanglement may result in severe injury or individual mortality via tissue damage, starvation, or drowning (Cassoff et al., 2011). Avoiding wind farm placement in areas of high whale population abundance is thus a key goal for responsible offshore wind energy development (BOEM 2024a).

The Central Coast offshore region also is frequented by numerous seabird species, including albatross, shearwater, storm-petrel, and pelicans, among others (Drew et al., 2005; DataBasin, 2024). While in flight, these birds may face the danger of collision mortality from, and displacement by, the turbines (Desholm et al., 2006; Wilson et al., 2007; Furness et al., 2013, 2017; Thaxter et al., 2017). Some of these species are of population conservation concern and/or they exhibit flight behaviors (e.g., elevation, turning radius) that may make them particularly vulnerable to offshore wind turbines (Adams et al., 2017; CDFW, 2023).

A literature synthesis of the environmental impacts of deepwater floating offshore wind farms found their potential effects on marine species, habitats, and ecosystem processes to likely be only minor to moderate (Farr et al., 2021); however, the synthesis was informed almost exclusively by research on analogous technologies such as fixed-bottom offshore wind turbines, oil and gas platforms, and marine energy devices (Farr et al., 2021). Also, among the six impact categories evaluated, the potential for turbines to generate structural impediments that increase avoidance, displacement, collision, and entanglement risk for marine seabirds and mammals was found to have the greatest potential environmental impact (Farr et al., 2021). A subsequent review found impacts on birds by offshore wind farms to almost always be negative and often high to moderate in magnitude, and impacts on marine mammals to typically be negative and sometimes with moderate to high magnitude (Galparsoro et al., 2022). Consequently, development of offshore wind along the Central Coast could impose a significant impact on marine wildlife conservation. Understanding the population vulnerability of these species to wind turbines, and incorporating that information into site selection processes for wind facility development, may help support both renewable energy and conservation objectives (Croll et al., 2022).

Spatial planning research estimates that wind energy facilities can be sited in the ocean and be compatible with other ocean activities and ecosystem service objectives, within certain constraints. When sited strategically and limited in its total footprint, a wind facility can generate minimal impacts to fisheries and marine conservation (White et al., 2012). Importantly, low-impact, high-value plans for offshore wind energy development – and other activities requiring ocean space, such as offshore aquaculture – can be identified using a quantitative tradeoff analysis that incorporates spatial models of the value of ocean ecosystem services to different sectors (stakeholder groups). This analysis identifies planning solutions that protect high-value sites to the sectors while also avoiding their overlapping spatial conflicts in the ocean in order to efficiently balance the sectors' objectives (White et al., 2012; Lester et al. 2013, 2018a).

Here we build on this legacy of spatial planning research and apply it to the Morro Bay WEA in relation to renewable energy industry, commercial fisheries, and seabird and cetacean (whale, dolphin, porpoise) conservation interests. We utilize existing and generate new spatial data layers for representing socio-economic activities in and around the WEA by these two economic activities and two wildlife groups (hereafter referred to as sectors): "Energy", "Fisheries", "Seabirds", and "Cetaceans". Using these data, we quantify each sector's response to wind energy development at both the individual turbine site level and at the aggregated turbine wind farm level, within each lease, and across the entire WEA. We then integrate these response estimates into a tradeoff analysis to compare the efficiency of the three leases at balancing the goal of high power production from wind energy with fisheries and wildlife conservation objectives. Using the tradeoff analysis, we also generate novel spatial plans of energy development (farm size, location, and configuration) for achieving target power production levels while minimizing, to the greatest extent possible, conflicts with fisheries value and wildlife conservation. These results can inform the site evaluation and permitting process for wind energy development in the Morro Bay WEA. We also anticipate our approach to provide an analytical framework for supporting the rapidly growing need for marine spatial planning of offshore wind energy development in the U.S. and elsewhere from a balanced perspective that values renewable energy production alongside existing socio-economic and conservation interests in the ocean.

2. Methods

We gridded the WEA into $I = 235$ patches 2×2 km in size (thus $Area_i = 4$ km^2), corresponding with a spatial resolution for supporting one offshore floating wind energy turbine per patch (following Wang et al., 2019b, and similar to Wang et al., 2022a). In each patch we considered two management options ($P = 2$): $p_{i=1}$, no wind energy development (i.e., status quo); and, $p_{i=2}$, development of a floating turbine and the mooring, cable tether, and platform infrastructure system for supporting it.

2.1. Sector responses

Below we describe the data sources and transformations conducted to estimate $R_{s,i,p}$, the response (R) by each sector (s) to the two potential management options (p) in each patch (i).

2.1.1. Energy

The wind energy sector value was represented by mean MW power production by each turbine in each patch, estimated using an atmospheric model and power curve detailed in Wang et al. (2019b). Briefly, hourly wind speed and direction at 2-km horizontal resolution at the sea surface and altitudes up to 200 m were estimated for 2007 through 2013 using WIND Toolkit. This is a simulated historical dataset validated by meteorological buoy measurements and determined, through comparison with other wind products, to be the best dataset for offshore wind energy production estimates for the central California coast (Wang et al., 2019a). The 2-km resolution of the model defined the patches used in this study (i.e., i). Turbine hub-height air density and interpolated wind speed at hub height were calculated to estimate effective hourly wind speed at 125 m altitude in each patch. Power production of a turbine in a patch was subsequently estimated by combining the wind data with a power curve (power output as a function of wind speed at hub height) for a 12-MW capacity turbine with 125 m hub height (Musial et al., 2016a; Wang et al., 2019b).

The high temporal (1-hr) resolution of the power data by Wang et al. (2019b) used in this analysis provides a more realistic estimate of mean power production in relation to the potential location of specific wind facilities. This is because estimates of mean power production can be significantly biased when using mean wind speeds to calculate mean power (versus calculating power at all times and then taking the mean power, as done here), leading to potentially inaccurate predictions about locations that are expected to produce the most power (Wang et al., 2019b). Also, the high spatial resolution of our analysis is sufficient to capture the down-wind spacing predicted for next-generation offshore floating wind turbines (Musial et al., 2016b) (A. Weinstein, CEO, Trident Winds, personal communication, 29 May 2018). This ensures that the resolution of the patches in our analysis can accurately account for various turbine array configurations.

Mean power production in megawatts (MW) was calculated across the hourly 7-year dataset for each patch and assigned to $R_{s=Energy,i,p=2}$. The energy sector's response to no development in a patch ($p = 1$) was set to zero ($R_{s=Energy,i,p=1} = 0$).

2.1.2. Fisheries

The fisheries sector was represented by mean total annual revenue (ex-vessel value) by commercial groundfish fisheries in each patch, estimated by Wang et al. (2024) using California Department of Fish and Wildlife (CDFW) fish ticket landings data and National Oceanic and Atmospheric Administration (NOAA) Vessel Monitoring System (VMS) vessel tracking data. Groundfish fisheries represent the highest value commercial fisheries in the Morro Bay WEA in terms of total annual biomass landings and ex-vessel value (Wang et al., 2022b), and VMS transceivers that indicate vessel identification number, location, speed, and other factors are required for commercial groundfish fisheries vessels operating in the WEA.

Briefly, Wang et al. (2024) analyzed VMS data from 2010 to 2017 to identify, precisely locate and time-stamp individual events of active fishing by commercial groundfish fisheries vessels, generating a map of the spatial distribution of fisheries effort throughout the US West Coast Exclusive Economic Zone (EEZ), including within the WEA. Following methods by Wang et al. (2022b), Wang et al. (2024) also analyzed CDFW fish ticket data (i.e., dock-side landings and price reports), for the commercial groundfish fisheries over the same study period. Revenue of the catch landed was calculated by multiplying the landing weight in pounds by the inflation-adjusted unit price reported on each fish ticket (Wang et al., 2022b).

Wang et al. (2024) then used unique vessel identification numbers and time-stamp data to link the fish ticket and VMS datasets, proportionally distribute the fisheries revenue from fish ticket reports to individual fishing trips identified from the VMS data, and generate highly resolved spatial distributions of groundfish fisheries revenue in California (Wang et al., 2024).

In Wang et al. (2024), total annual revenue was calculated by aggregating the revenue from each year within lease blocks, which are represented as 4.8 km × 4.8 km polygons that cover the study domain and were defined by BOEM. The mean total annual revenue was then obtained by averaging the total annual revenue over the 8-year (2010–2017) fisheries dataset for each lease block. In this study, we matched each 235 4 km^2 patch in the WEA to the lease block within which its centroid was positioned, then assigned the mean total annual revenue of the lease block to the patch.

Mean total annual revenue for each patch was assumed to represent the spatially-explicit value of each patch to the fishery sector under no development (status quo) and was thus assigned to $R_{s=Fishery,i,p=1}$. Commercial groundfish fishing may be restricted and/or impractical (due to gear entanglement) near a floating wind turbine and its associated infrastructure (undersea cables and mooring), thereby reducing fishery value in that area to $R_{s=Fishery,i,p=2} = \theta R_{s=Fishery,i,p=1}$, where $1 > \theta = 0$. However, the distance and degree to which fishing is displaced is uncertain and likely to vary in relation to turbine infrastructure design and fishing gear technology (Alexander et al., 2013; Gray et al., 2016). To account for this uncertainty, we set $\theta = 0.25$ as a baseline scenario (fishery value in a patch with a turbine is reduced to 25% its status quo level), and also considered $\theta = 0.5$ and $\theta = 0$ to represent more moderate and extreme impacts. We applied θ to all patches in the WEA because they are relatively uniform in habitat type (soft bottom; Cochrane et al., 2022) and fished almost exclusively by the same fishery type (commercial groundfish; Wang et al., 2024).

2.1.3. Marine wildlife conservation sectors

To estimate potential levels of vulnerability of populations of marine wildlife to wind farm development, we integrated empirical survey data characterizing the spatial distribution and abundance across the seascape of populations of seabirds (Class Aves) and cetaceans (whales, dolphins and porpoises; Infraorder Cetacea) with estimates of their population status and potential behavioral and population-level interactions with wind facilities. We assessed seabird and cetacean vulnerability metrics individually to identify and map potentially different spatial responses by each sector to wind farm development.

2.1.3.1. Seabirds. Seabird species relative mean population densities in and around the Morro Bay WEA were estimated using the North Pacific Pelagic Seabird Database (NPPSD; Drew et al., 2005). NPPSD is managed by the US Geological Survey (USGS) and is compiled from hundreds of thousands of at-sea biological transect surveys conducted to census seabirds. The database contains abundance and distribution information on over 20 million birds comprising over 250 species surveyed over many decades in the North Pacific, including California Central Coast continental shelf waters.

We followed guidelines provided by USGS for filtering the NPPSD appropriately for our analysis (G. Drew, USGS, personal communication, October 31, 2020). We filtered the NPPSD to include all living birds identified to species by boat-based transect surveys with position data (latitude, longitude) and a reported transect survey area (for estimating relative bird population density). Surveys conducted before 1991 were excluded because position data was typically limited to the starting location of the vessel trip (e.g., at or near port), as opposed to the centroid of the transect survey (as done starting in 1991). To focus on the biophysical ecosystem within and around the WEA, we further filtered the data to transects conducted along the California Central Coast, defined here as Monterey Bay (36.811 N, 121.83 W) to Point Conception (34.4486 N, 120.4716 W). We further refined data to federal waters (3 nautical miles from the coast) extending out to 123 W, corresponding with the western boundary used previously for assessing offshore winds and power generation (Wang et al. 2019a,b). We used ver. 4 of the NPPSD (the most current), which covers up through 2021.

We overlaid the study domain encompassing the filtered NPPSD data with a grid of 4 km^2 cells corresponding with those defined by Wang et al. (2019b), which includes the 235 patches in the WEA. We then assigned each NPPSD transect survey to the grid cell within which its centroid position was located. For each grid cell, we averaged across surveys to calculate the mean relative population density for each seabird species in each year of the 31-year NPPSD dataset (1991–2021). To reduce sampling error, we focused on grid cells with at least 10 years of survey data. To determine the sensitivity of our results to this filtering step, we also reran our analysis with consideration of grid cells with fewer than 10 years survey data. For each species and grid cell, we then calculated its mean relative population density across years.

Adams et al. (2017) quantified population and collision vulnerability levels of marine birds to offshore wind energy facilities (if installed) in the California Current Ecosystem (CCE), based on bird species population biology and behavior. Species population biology included population size, proportion of its population in the CCE, conservation threat status, and breeding and survival demographic variables; bird species behavior included nocturnal and diurnal flight activity, macro-avoidance behavior of turbines, flight height, and presence in the rotor swept zone. These vulnerability assessments were generated in order to be combined with marine seabird at-sea distribution and abundance data to evaluate vulnerability areas where offshore wind energy development is being considered (Adams et al., 2017). Accordingly, we integrated these species-specific vulnerability estimates with the spatially-explicit (grid cell) species population density estimates from the NPPSD to estimate vulnerability levels of seabirds to turbine development across the seascape. Specifically, in each grid cell we multiplied the mean relative population density of each seabird species by the species' population collision vulnerability (PCV) score estimated by Adams et al. (2017). Species in the NPPSD without a PCV score were given the median PCV score calculated across the species in the analysis with a PCV score; to determine the sensitivity of our results to this assumption we also ran our analysis excluding species without a PCV score. For each grid cell, we then summed the (population density)-by-PCV value across species to generate a composite metric estimating the relative level of seabird population vulnerability to turbine development in a grid cell along the California Central Coast.

To reduce bias due to short (thus small area) transect surveys in some grid cells (that can produce spuriously high seabird population densities) we removed outliers, defined as cells with vulnerability levels more than three scaled median absolute deviations from the median level among all the grid cells. We also performed the tradeoff analysis without removing any outlier grid cells to determine the sensitivity of the results to this assumption.

The remaining grid cells cover only a portion of the California central coast study domain, and not all 235 patches in the WEA. However, seabird vulnerability to offshore wind farms has been found to decline steeply with distance offshore (Garthe and Huppop, 2004; Bradbury et al., 2014; Best and Halpin, 2019; Critchley and Jessopp, 2019). Thus, we used the grid cells with estimates to generate a model of seabird vulnerability that could be applied to patches in the WEA. Using linear regression and a significance value of $\alpha = 0.05$, we tested for a functional relationship between seabird vulnerability in a grid cell and the natural log of the cell's distance from shore. Given statistical significance, we then applied the function to the grid cells in the WEA (i.e., $I = 235$ patches) in relation to their distance from shore. The model estimates of potential, relative vulnerability of seabirds to the presence of a wind energy turbine in a patch was then assigned to represent the response of the seabird conservation sector to energy development, $R_{s=Seabirds,i,p=2}$. The vulnerability response by the seabird sector to no development (status quo) in a patch ($p = 1$) was set to zero ($R_{s=Seabirds,i,p=1} = 0$).

2.1.3.2. Cetaceans. Relative mean population densities in and around the WEA were estimated using outputs of species distribution models (SDM) of surface population densities of whales, dolphins and porpoises in the CCE developed by Becker et al. (2020). Briefly, a Generalized Additive Modeling framework was used by Becker et al. (2020) to develop the SDMs based on shipboard line-transect surveys and dynamic habitat variables from a Regional Ocean Modeling System (ROMS), including sea surface temperature, mixed layer depth, sea surface height, ocean depth, and distance to continental shelf break and continental rise undersea features. The models were developed for 13 cetaceans (five whale, seven dolphin, one porpoise species) using 92,214 km of survey data collected between 1996 and 2018, and they provide spatially-explicit, multi-year (23-year) average relative population density predictions at a 0.1° (approximately 10 km by 10 km) grid resolution (Becker et al., 2020).

To account for differences among species in their population and entanglement vulnerability to offshore wind facilities, we applied species-specific weights to the average relative population density predictions generated by the SDM. Two weighting scenarios were based on population conservation status (sensu Farmer et al., 2023). Representing the baseline scenario, we weighted the species equally, given that all 13 are protected by the Marine Mammal Protection Act (MMPA) and listed under CITES Appendix I or II (NOAA 2022). In a second weighting scenario, we focused on species of especially high population conservation concern by excluding all but three species in the SDM that are listed as Endangered under the Endangered Species Act (ESA) and/or Depleted under the MMPA (blue whale, *Balaenoptera musculus*; fin whale, *B. physalus*; and humpback whale, *Megaptera novaeangliae*), and weighted them equally. A third weighting scenario was based on morphological and behavioral traits. Baleen whales may be particularly vulnerable to (primary, secondary, and tertiary) entanglement by cables and other infrastructure associated with turbines, because they forage by swimming through or engulfing dense concentrations of prey with their mouths open, thus exposing themselves to entanglement across the mouth, where entangled gear can become captured amongst the baleen and especially difficult to dislodge (Benjamins et al., 2014 and references therein). Also, large cetaceans may be particularly vulnerable because they can be attracted to turbine cables and infrastructure in search of a solid surface to scratch themselves against to remove dead skin and/or parasites, and entanglement is more likely for animals attracted to the facility (Benjamins et al., 2014). To focus on these vulnerabilities, we excluded dolphins and porpoises and weighted equally the five whale species, all of which can reach lengths greater than 10 m (minke, *B. acutorostrata*; Baird's beaked, *Berardius bairdii*; blue, fin and humpback). All but the Baird's beaked whale also are baleen whales. These weighting scenarios are not meant to precisely represent the true relative vulnerability levels of cetacean species; instead, they are considered to test the sensitivity of the tradeoff analysis to the range of vulnerabilities possible. For each scenario, we multiplied the weight for each species by its relative population density prediction at each 0.1° point in the SDM. For each point, we then summed the (population density)-by-weight value across species to generate a composite metric estimating the relative level of cetacean population vulnerability to turbine development at each point along the California central coast.

To apply the cetacean data to the scale of potential turbine development in the WEA, we conducted linear interpolation of cetacean population vulnerability at the SDM points (0.1° resolution) to the 4 km^2 grid cells in the study domain. This downscaling in spatial resolution was possible due to the smooth distribution of SDM values across the study area. We then selected the grid cells in the WEA representing the $I = 235$ patches used in the tradeoff analysis. The estimate of potential, relative vulnerability of cetaceans to developing a wind energy turbine in a patch was then assigned to represent the cetacean conservation sector under the develop management option, $R_{s=Cetacean,i,p=2}$. The vulnerability response by the cetacean sector to no development (status quo) in a patch ($p = 1$) was set to zero ($R_{s=Cetacean,i,p=1} = 0$).

2.2. Tradeoff analysis

The key goal of tradeoff analysis is to identify optimal management options that maximize multiple sectors' objectives simultaneously, to the extent possible (Lester et al., 2013). Because society may place different priorities on different objectives, an optimal management option depends on the relative weighted value of the sectors' objectives. Consideration of the full set of relative weights, ranging from full priority for a particular objective to a balanced prioritization among the objectives, generates an efficiency frontier of a set of optimal management options that each best balances the sector's weighted objectives (for a discussion of the efficiency frontier, see Lester et al., 2013; Stevens et al., 2018).

We conducted tradeoff analysis on all combinations of pairs of sectors, generating a set of $S!/[2!(S-2)!] = 6$ two-dimensional pairwise efficiency frontiers for the $S = 4$ sectors ("Energy", "Fisheries", "Seabird", and "Cetacean").

In the case here of only two management options possible in each patch (e.g., status quo or develop; i.e., $p = 1$ or 2, respectively), the efficiency frontier of spatial plans can be computed highly efficiently using ratio analysis (Oleson et al., 2017). First, the change in response by sector (s) to a change in management in patch (i) from option $p = 1$ to option $p = 2$ is calculated:

$$R_{s,i,\Delta p} = R_{s,i,p=2} - R_{s,i,p=1} \tag{1}$$

For each sector, its change in response determines a numerator (N_i) or denominator (D_i) parameter to be used in a ratio. Given the sector benefits from $p = 2$ over $p = 1$: if the sector response is a value and higher with $p = 2$, then $N_i = R_{s,i,\Delta p}$; if the sector response is an impact and lower with $p = 2$, then $N_i = |R_{s,i,\Delta p}|$. Given the sector loses from $p = 2$ over $p = 1$: if the sector response is a value and higher with $p = 1$, then $D_i = |R_{s,i,\Delta p}|$; if the sector response is an impact and higher with $p = 1$, then $D_i = R_{s,i,\Delta p}$.

If both sectors benefit from $p = 2$ in patch i, or one sector benefits and the other is unaffected, then there is no pairwise tradeoff and the patch is set to $p = 2$. And vice versa: if both sectors lose from $p = 2$, or one sector loses and the other is unaffected, then there is no tradeoff, and the patch is set to $p = 1$.

The energy sector change in response was set to the numerator because it benefits from $p = 2$ over $p = 1$, and is a value and higher with $p = 2$. The absolute value of the fisheries sector change in response was set as the denominator because the sector loses from $p = 2$ over $p = 1$, and its response is a value and higher with $p = 1$. Both the seabirds and cetaceans sector changes in response were set as denominators because the sectors lose from $p = 2$ over $p = 1$, and their responses are impacts and lower with $p = 1$.

The numerator and denominator parameters are indexed for just the patches where one sector benefits and the other loses from $p = 2$ (i.e., there is a tradeoff):

$$N_t = N_{i(Tradeoff)} \tag{2}$$

$$D_t = D_{i(Tradeoff)} \tag{3}$$

The ratio of their response change is then calculated as

$$O_t = N_t / D_t \tag{4}$$

O_t is a positive number (i.e., $0 < O_t < \infty$), and $\mathbf{O_T}$ is a vector of sector response ratios of length T, the number of patches with tradeoffs ($T \leq I$).

To identify the full set of spatial plans on the efficiency frontier (EF) that optimally mediate the pairwise sector tradeoff, the ratios in $\mathbf{O_T}$ are ranked in descending order, $O_q = Rank(O_t, descend)$, where q is the rank order of patch t. Then, $T + 1$ optimal spatial management plans are determined by iterating over the ranked order of patches. For $v = 1, 2, 3, \ldots, T + 1$,

$$EF_{v,s=x,s=y} = \begin{cases} p = 1 & \textit{for patch } t = \mathbf{q}(v), \mathbf{q}(v+1), \mathbf{q}(v+2)\ldots, \mathbf{q}(T) \\ p = 2 & \textit{for patch } t = \mathbf{q}(0), \mathbf{q}(1), \mathbf{q}(2)\ldots, \mathbf{q}(v-1)) \end{cases} \tag{5}$$

where $\mathbf{q}$ is a vector of the patch rank order, and x and y represent the pair of sectors being analyzed. Increasing values of v thus represent spatial plans with a greater number of patches with management option $p = 2$ over $p = 1$.

Recall, for patches without a pairwise tradeoff (i.e., $i \notin \mathbf{T}$) the management option $p = 1$ or $p = 2$ is set *a priori* for every optimal spatial plan. Thus, each solution $EF_{v,s=x,s=y}$ is an integer vector representing a spatial plan of the entire study domain (including "fixed" patches), indicating the optimal management option in each patch *i*, given *v*.

We conducted tradeoff analysis at two spatial scales. At the larger scale, we applied tradeoff analysis to all $I = 235$ patches in the WEA to assess the efficiency with which wind farm development could be planned across the entire area (unrestricted by the lease block borders) with minimal impacts on the fisheries and wildlife conservation sectors. Additionally, we calculated sector responses to full development within each lease and compared these outcomes to each other and the WEA-wide efficiency frontier to quantify the relative efficacy of each lease in maximizing power production while minimizing fisheries and wildlife conservation impacts.

At the smaller scale, we applied tradeoff analysis to an individual lease to identify spatial planning solutions within that area that minimally compromise energy value while maximally recouping fisheries and wildlife conservation impacts relative to if the lease were fully developed. We focused on the tradeoff of the energy sector with the fisheries sector, which was found to have a highly heterogeneous spatial distribution of value across the lease (see Results), indicating there to be strong potential for its impact to be mediated by strategic spatial planning (Lester et al., 2013).

Useful for a planning process is the ability for managers and sectors to compare a small number of distinct or "seed" spatial planning solutions (Lester et al., 2018c). Accordingly, to maximize the applied value of this study, we considered energy sector targets of 75%, 90% and 95% of its total value (cumulative MW power production) in each lease area. For each target, we identified the optimal spatial plan on the efficiency frontier that minimized loss in value to the fisheries sector, as well as quantified the response of all four of the sectors. We also generated maps of the spatial plans (wind farm size, location and configuration within the lease) to provide practical guidance to decision-makers. These plans demonstrate ways to meet a specific energy industry goal while minimizing conflicts with other sectors, and thus could be used to support deliberation among sectors, and between sectors and BOEM, in determining actual development plans to pursue and permit.

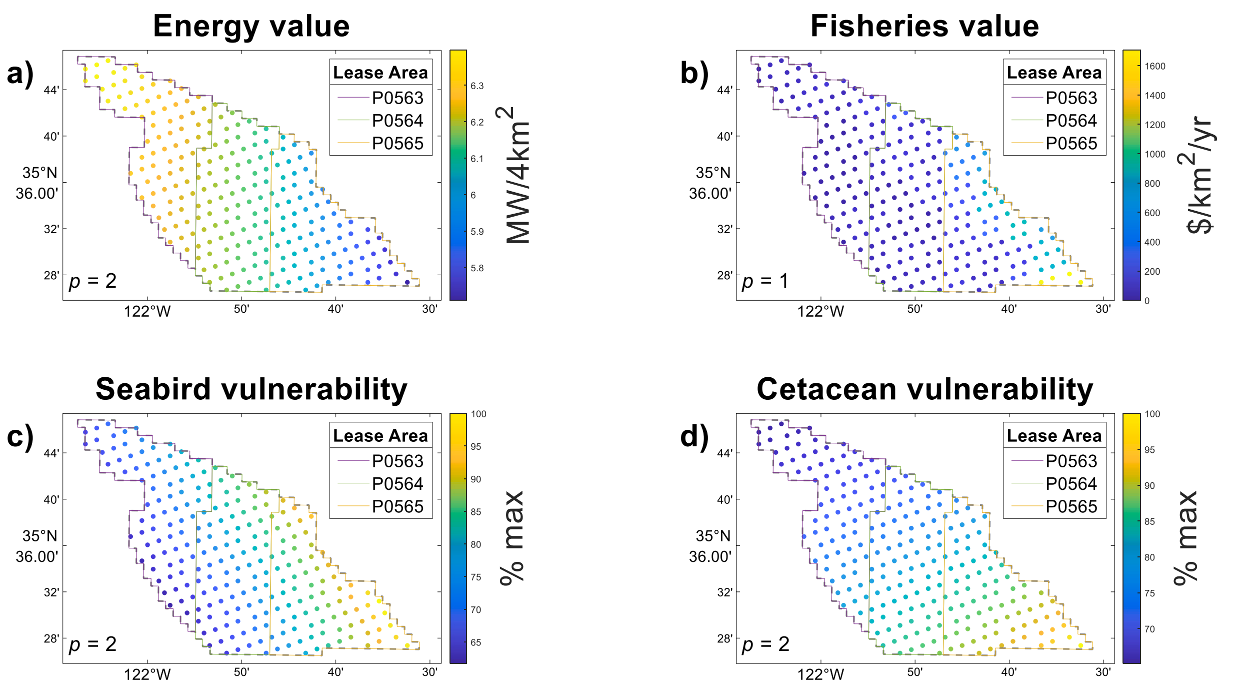

Fig. 2. Sector responses to wind energy turbine development throughout the WEA, inclusive of the three wind energy lease areas (see legend). Circles in the maps represent potential turbine locations. a) Power generation ($R_{s=Energy,i,p=2}$). b) Status quo fisheries value without development ($R_{s=Fishery,i,p=1}$), which is reduced proportionally by θ ($1 > \theta = 0$) if a patch is developed for energy. c-d) Vulnerability of seabird and cetacean populations to energy development ($R_{s=Seabirds,i,p=2}$ and $R_{s=Cetacean,i,p=2}$). Overall, potential power production is highest in the northwestern region of the WEA farthest from shore, while potential loss in fisheries value and vulnerability of seabird and cetacean populations is highest in the eastern region of the WEA closest to shore.

3. Results

3.1. Sector responses

All four sectors varied spatially in their response to wind energy development in the WEA. Estimated power generation at a potential turbine site increased to the northwest (Fig. 2a), potential loss in fisheries revenue from displacement around a turbine increased to the southeast (Fig. 2b), and vulnerability of seabird and cetacean populations to a turbine increased to the east (Fig. 2cd). In general, western sites farthest from shore maximized power production while minimizing impacts to the other sectors, and vice versa in the eastern sites closest to shore (Fig. 2). Detailed results from the generation of the response layers for the seabird and cetacean sectors are provided in the Supplemental Information text and Fig. S1-4.

Sector response to wind farm development in a lease to capacity varied among leases and by sector. The energy sector was minimally sensitive to which lease area was developed – each lease can generate similar levels of MW power if fully populated with turbines (Fig. 3a). The fisheries sector experienced the same proportional loss in value in each lease from wind farm development (as dictated by θ), but varied substantially in the magnitude of fisheries value lost and value remaining with development. In particular, the eastern lease (P0565) hosts substantially more status quo fisheries value than the other two leases (Fig. 3b solid bars), and, consequently, it stands to lose 7–10 times more \$/yr in fisheries value from development compared with the loss expected in the other leases (Fig. 3b solid bar minus hatched bar). However, despite P0565 losing the most fisheries value, what remained in value in that lease exceeds that in the other leases (Fig. 3b hatched bars), because it started off with the highest status quo value without development.

The response by the two wildlife conservation sectors to wind farm development differed moderately among the three leases in relation to cardinal direction and distance from shore. Vulnerability of both seabird and cetacean populations to development was approximately similar across the three leases (~30–40% of total vulnerability in the WEA), but was consistently highest in the eastern lease (closest to shore), lower in the central lease, and lower still in the western lease (farthest from shore) (Fig. 3cd).

Overall, the four sectors' objectives were best met by development of the western lease (P0563) farthest from shore, because it generated nearly the greatest power and resulted in the fishery retaining its highest value and the wildlife sectors exhibiting their lowest vulnerabilities. In contrast, the sectors' objectives were least met by development of the eastern lease area (P0565) closest to shore because, despite it still generating high power, development there reduced fisheries value and increased seabird and cetacean vulnerability the greatest.

3.2. Tradeoff analysis

Pairwise efficiency frontiers of optimal spatial plans of wind farm development across the entire WEA differed dramatically

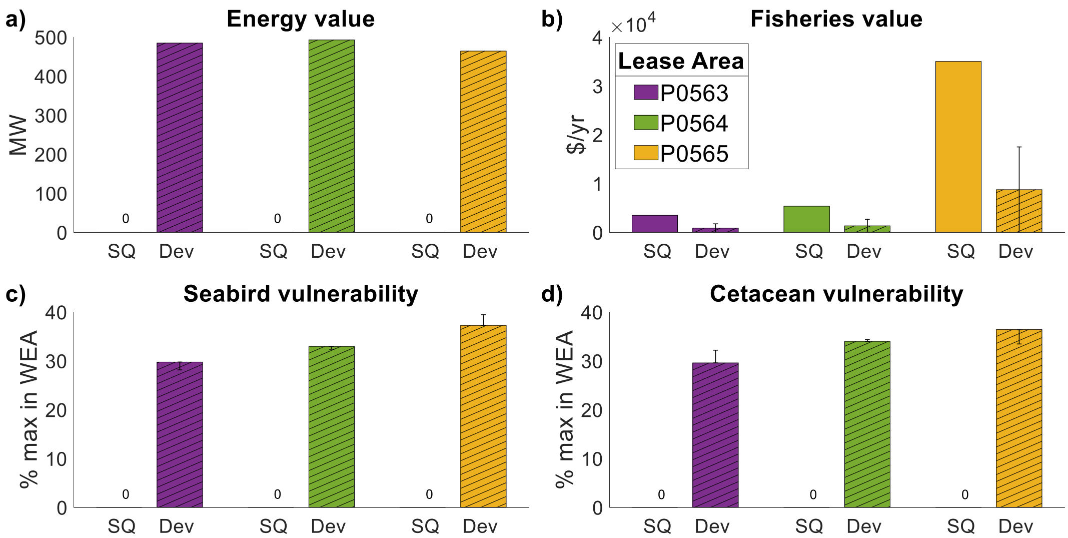

Fig. 3. Cumulative sector response across all patches in a lease to no development (status quo, SQ) and development of the lease to full capacity (Dev). a) Gain in energy sector value (potential power generation) is similar across leases. b) Status quo fisheries sector value, and loss in value from energy development, is similar in leases P0563 (farthest west) or P0564 (central), and much less than in lease P0565 (farthest east); however, remaining fisheries value with energy development is potentially higher in P0565 (given $\theta > 0$). c) Potential vulnerability of seabird and cetacean populations to energy development varied moderately among the leases and was highest in P0565 and lowest in P0563. Bars represent the baseline scenario, and fences indicate the minimum and maximum sector response levels across all parameter values evaluated (see Methods). Note that the fences should not be confused with error bars (indicating statistical variance) or used in a test of statistical significance (White et al., 2014); overlapping fences by bars in the same plot do not support a null hypothesis of no difference.

between the energy-fisheries vs. energy-wildlife sectors. The energy-fisheries efficiency frontier was strongly convex (Fig. 4a), indicating substantial opportunity to mitigate the tradeoff and generate high energy value with low fisheries loss through strategic spatial planning of turbines in patches that are high in potential energy value (Fig. 2a) and/or low in status quo fisheries value (Fig. 2b). In contrast, the energy-seabird and energy-cetacean efficiency frontiers were weakly convex (Fig. 4BCE), indicating only a moderate ability to reduce their tradeoffs from strategic spatial planning.

Evaluation of the three leases in the tradeoff plots revealed wind farm development of the western lease farthest from shore (P5063) to nearly optimally mitigate, to the extent possible, the tradeoff between the energy sector and the fisheries, seabird, and cetacean sectors (Fig. 4 triangles close to the efficiency frontiers). The central lease (P0564) also efficiently balanced the sectors' objectives (Fig. 4 squares), though not quite as well as P5063. The eastern lease closest to shore (P0565), in contrast, represented a spatial plan of wind farm development that was consistently inferior at balancing the objectives relative to the efficiency frontier and the other two leases, especially for the energy-fisheries tradeoff (Fig. 4 circles). In that case, development of P0565 reduced the fisheries sector to a value in the WEA that was approximately 40% what it would achieve if either of the other leases were instead developed, or an optimal spatial plan was developed across the WEA that generated the same power as that by P0565.

Energy-fisheries tradeoff analysis conducted at the scale of each lease revealed strongly convex efficiency frontiers (Fig. 5), indicating opportunities to prevent large losses in fisheries value concurrent with only small foregone gains in MW power (Lester et al., 2013). For example, wind farm development in the eastern lease (P0565) to 95% instead of a full 100% of the lease's power generation capacity could prevent a 15% loss in fisheries value, raising the fisheries sector's total value in the lease from 25% to 40% (Fig. 5c). Similar low-fisheries loss outcomes in the lease could be achieved for other high-energy value targets: 90% energy value (i.e., foregoing 10% total power production in the lease) could prevent 22% in losses in fisheries value, enabling the fisheries sector to maintain half its status quo value (Fig. 5c). Further up the efficiency frontier, strategic spatial planning enables an energy target of 75% its maximum value to support the fisheries sector achieving 66% its maximum value (Fig. 5c). In the western (P0563) and central (P0564) leases, similar proportions of fisheries value could be saved with only low to moderate losses in energy value (Fig. 5ab). The absolute savings in fisheries value ($/yr) were much less than that in the eastern lease, though, due to the western and central leases having much lower total status quo fisheries values (Fig. 3b). Overall, the lease-scale efficiency frontiers indicate that out-sized savings in fisheries value can be achieved by small to modest losses in MW power through strategic spatial planning.

Mapped spatial plans of wind farm development (turbine number and location) associated with solutions along the efficiency frontiers revealed patches to target and avoid for turbine placement for mitigating the energy-fisheries tradeoff. For the eastern lease (P0565), its offshore western edge is consistently identified for development (Fig. 5ci-iii), due to the relatively high power generation potential and low status quo fisheries value in that area (Fig. 2ab). Conversely, the southeastern corner of the lease is consistently avoided for development (Fig. 5ci-iii), due to lower power generation potential and an especially high status quo fisheries value there (Fig. 2ab). Avoiding this corner area – representing just 5 patches in the 78-patch lease – achieves 95% of the power sector's value and maintains 40% of the fisheries sector's value in the lease (Fig. 5ciii). Beyond that, maintaining half the fisheries value in the lease while achieving 90% power value reveals a second area of patches along the northeastern edge of the lease to be avoided for development (Fig. 5cii). Protection from turbine development in these two areas is expanded upon to realize further savings in fisheries value concurrent with modest losses in power value (Fig. 5ci). Mapped spatial plans associated with solutions on efficiency frontiers for the western (P0563) and central (P0564) leases also revealed consistent areas for development, mainly in the southern and western areas of each lease, and to avoid, in the northern region of each lease (Fig. 5ai-iii and 5bi-iii).

Extremely low levels of fisheries value (<0.1 $/yr) found in 16 patches in the WEA (Fig. 2b darkest blue circles) contributed toward

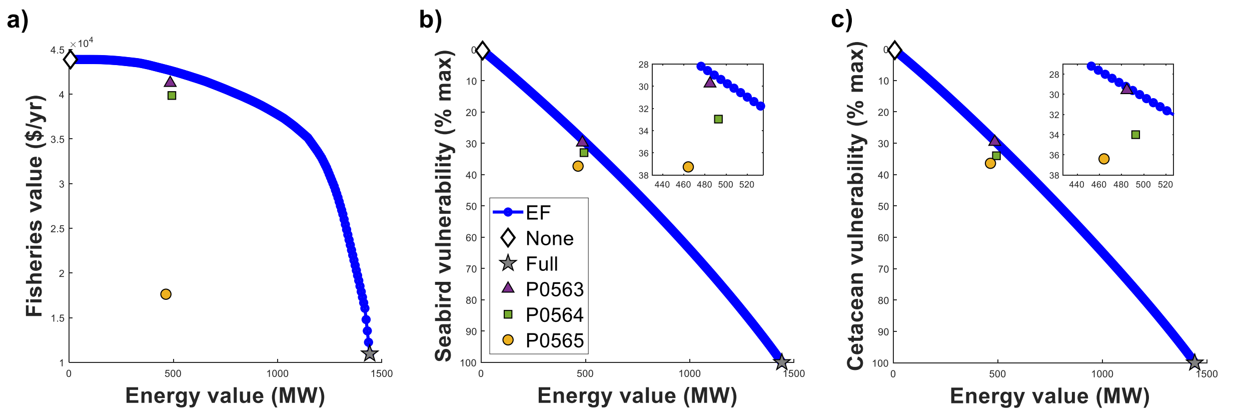

Fig. 4. Pairwise efficiency frontiers (EF) of spatial plans across the entire WEA that minimize tradeoffs between sector objectives, compared with outcomes from wind farm development in each of the three wind energy leases. Efficiency frontiers minimize the tradeoff between each pair of sectors, representing $I + 1 = 236$ spatial plans of wind farm development represented by 0, 1, 2, 3, ….235 patches with a turbine; i.e., "None" (top left) to "Full" (bottom right) development of the WEA. Symbols inside the efficiency frontiers represent outcomes from development of each lease to full capacity (see legend in panel b, which applies to all three panels). Insets show zoomed-in views of the data. Pairwise efficiency frontiers among fisheries, seabird and cetacean sectors are not shown, because they are represented by a single management plan with no wind farm development because their objectives are all negatively impacted by wind farm development.

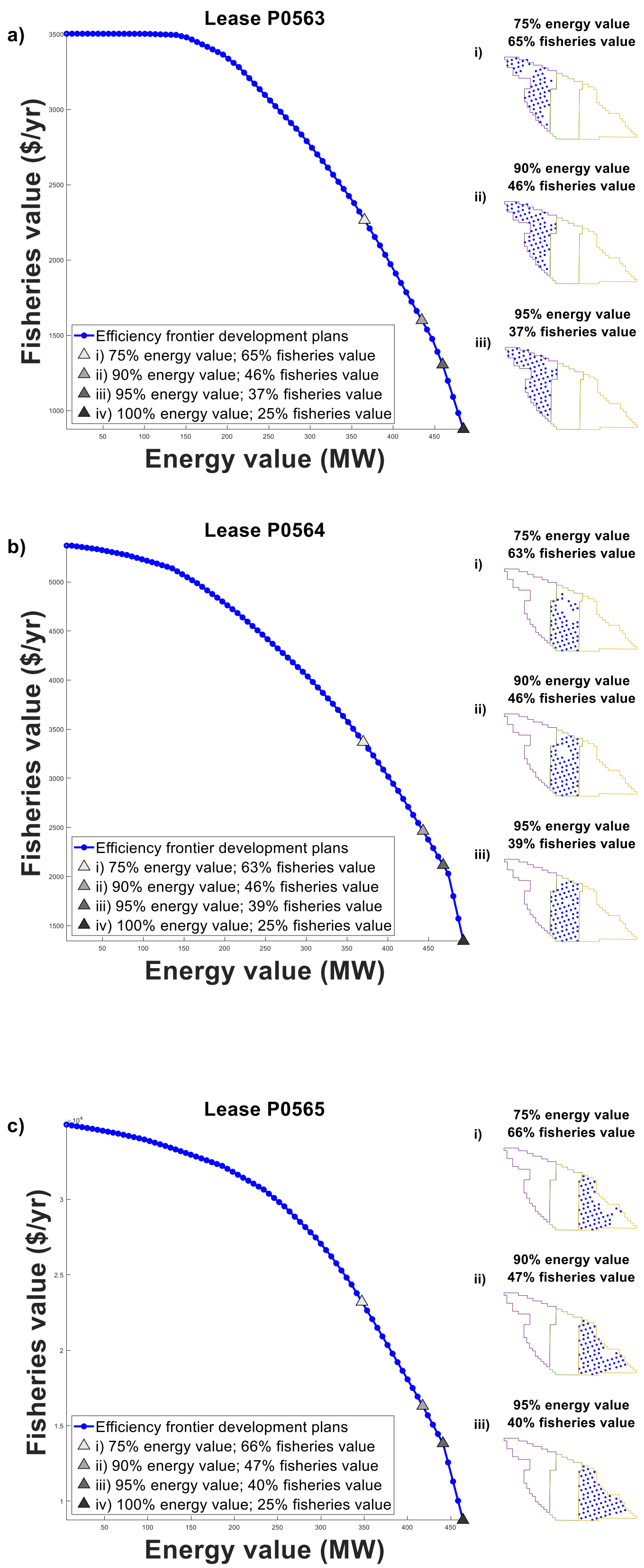

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Fig. 5. Efficiency frontier of spatial plans of wind farm development in each lease that minimize the tradeoff between energy and fisheries sector objectives. Points on each efficiency frontier represent establishment of turbines in none to all of patches in the lease, representing 0–100% energy development. Triangles and associated maps represent example levels of development along the steep edge of the efficiency frontier, where large gains/losses in fisheries value can be obtained/avoided with only a marginal loss in MW power. Baseline parameter values used.

the energy-fisheries efficiency frontier being much more convex than the energy-seabird and energy-cetacean frontiers (Fig. 4). This is because the fisheries value was nearly perfectly horizontal (e.g., approximately unchanged) along the energy value axis going from zero power (no wind farm development) to approximately 100 MW, or 7% of the total power potential in the WEA (Fig. 4a). The pattern is enhanced for the energy-fisheries tradeoff plot of the western lease (Fig. 5a, horizontal, upper left section of efficiency frontier), because all 16 patches are located in that lease (Fig. S5). In this case, the 16 patches represent 20% of both the lease's area and its total potential power production. Furthermore, all except two of the patches are clustered together (Fig. S5). Consequently, a notable proportion of wind energy development in the WEA – in the western lease in particular – is estimated to be possible without inflicting an impact on the fisheries sector.

While consideration of our assumptions affected how strongly the fisheries, seabird, and cetacean sectors responded to offshore wind farm development (Fig. 3b–d bars and fences), it did not change a sector's relative spatial response to development across the WEA – potential loss in fisheries revenue and vulnerability of seabird and cetacean populations always increased in the eastern, nearshore direction. Consequently, the tradeoff analysis and spatial planning solutions were insensitive to our assumptions. Specifically, we considered: for the fisheries sector, the proportional value remaining in a patch following turbine development ($\theta = 0.5 - 1$); for the seabird sector, the minimum number of years a cell had to be surveyed by NPPSD to be included in the analysis (5–10), setting species with no PCV score as the median score vs. excluding them from the analysis, and removing or not cells with outlier vulnerability estimates; and, for the cetacean sector, weighting the species equally or in relation to conservation status, foraging behavior, or size. In all cases, the assumption did not affect the relative spatial pattern of sector response in the WEA, relative impact of wind farm development on the sector across the three leases, or the shape of the WEA-wide and lease-specific efficiency frontiers and associated spatial planning solutions. That is, results were qualitatively unchanged by the assumptions analyzed.

4. Discussion

Achieving a blue economy will require reconciling the value of emerging ocean uses with their impacts on the seascape and on sectors with historical access to marine resources and areas (Dundas et al., 2020). We show how marine spatial planning with tradeoff analysis can integrate models of interacting emerging and historical ocean sectors (energy, fisheries, and wildlife conservation) into a single analytical framework. We then demonstrate how the framework can be used to (i) quantify potential gains and losses in value to each sector in an area slated for wind energy development (the Morro Bay WEA), (ii) compare the efficiency of proposed development plans (of the western, central and eastern leases) at providing renewable energy while preserving the historical sectors' values, and, (iii) reveal novel spatial planning solutions (maps of wind farm size, location and configuration) that optimally meet targets (power production levels) for the emerging sector while minimizing, to the extent possible, impacts to the other sectors. Our results have immediate practical value for informing wind farm development and sectoral negotiation decisions in the Morro Bay WEA (de Groot et al., 2014). The analytical framework we derived also has broad value for supporting blue economy spatial planning and site evaluation processes elsewhere, including offshore wind farm projects in Oregon and offshore aquaculture in southern California and the Gulf of Mexico (NOAA, 2020, BOEM, 2024b).

While spatial planning with tradeoff analysis is not new (Polasky et al., 2008; White et al., 2012), the applied and universal value of the framework developed here is bolstered by the simplicity of both its analytical equations (algebra only) and use of spatial data layers (maps) for representing sector responses to management. As such, the framework is accessible to a broad audience, from scientists to managers to practitioners, and it can utilize the vast and rapidly growing supply of publicly-available geospatial data and models quantifying spatial patterns of resource distribution, use, and value (Coetzee et al., 2020; Mahrad et al., 2020; Taminia et al., 2020; Schwartz-Belkin and Portman 2023; USGS 2024). It also is not limited to marine applications, because the framework's basic principle of analyzing the distribution and overlap of spatial data layers representing resources and their use applies to the management of terrestrial systems as well (Solecka 2018).

In the Morro Bay WEA, positive fisheries revenue in almost all patches and positive seabird and cetacean population vulnerability levels throughout the WEA indicate there will be no free lunch for wind farm development there. However, the contrasting directional pattern of value of the historical sectors with the energy sector – higher power production in the west, higher fisheries revenue and wildlife vulnerability in the east – provides the opportunity for spatial planning to generate high power value with proportionally low impacts. This finding is dramatically clear for the fisheries sector, which suffers only minor losses in value in the WEA from development of the western (P0563) and/or central (P0564) leases, compared with losing more than half its total value were the eastern lease (P0565) to be fully developed. Incidentally, seabird and cetacean vulnerabilities were also highest in the eastern lease (though not dramatically so compared with the other two leases). Simply avoiding the eastern lease provides large savings to the fisheries sector, as well as the greatest support for wildlife conservation.

Strong spatial heterogeneity in fisheries value across the WEA – namely, a hotspot of revenue in the southeast corner and an area of near-zero fisheries activity near the western edge – generate the strong convex shape of the energy-fisheries efficiency frontiers that indicates high potential for balancing these two sectors' objectives with strategic spatial planning (Lester et al., 2013). Avoiding development in just a handful of patches in the eastern lease (P0565), for example, can maintain nearly half the fisheries' revenue in that lease. This and other promising spatial planning solutions that generate near-maximum power while maintaining moderate fisheries value are possible in all three leases and illustrated by the steep slope in the energy-fisheries efficiency frontier lines (lower right corner of tradeoff plots – Fig. 5). While the absolute economic savings to the fisheries sector (e.g., $10 ks/year in revenue) may be orders of magnitude smaller than the economic gains expected from a wind farm project in the WEA (in the billions of dollars; Hamilton et al., 2021), valuation of a fisheries sector extends beyond economics to include non-market metrics such as access to fishing grounds and maintaining its cultural heritage (Tallis et al., 2012; Ignatius et al., 2019; Coglan et al., 2020). Thus, the percentage gains in fisheries value reported here (>15%; Fig. 5) from reduced energy development likely represent a significant level of socio-cultural value to the fisheries sector. Development to less than full capacity may also be practical from the energy industry perspective, as indicated by numerous "complete" offshore wind farm projects in Europe that were not built to the full planned size (RenewableUK, 2017). Furthermore, marine spatial planning research suggests that even if these plans were modified somewhat to accommodate factors not considered in this analysis, they are still likely to produce near optimal outcomes (Rassweiler et al., 2014).

The flat, nearly horizontal slope on the other side of the efficiency frontiers (upper left corner of tradeoff plots) also indicates promising options, in this case for growing energy value at minimal cost to the fisheries sector. In the western lease (P0563) in particular, the horizontal section of its efficiency frontier illustrates how initial development of an approximately 60 km^2 rectangular zone (18% of its total area), perhaps by a pilot wind farm project or simply the first turbines put in place during what would likely be an extended project development period (Lerche et al., 2023), would have a negligible impact on the fisheries sector due to the near lack of groundfish fisheries activity in that entire zone. Furthermore, because the zone is in the western portion of WEA, its development would have a relatively low impact on the wildlife conservation sectors. Such a pilot project also would provide opportunities to develop environmental monitoring approaches and mitigation strategies that will be required with offshore wind energy development (CA-AB-525, 2021). Overall, the results indicate strategic spatial planning can have an important role in maximizing the gains and minimizing the costs of wind energy development in the Morro Bay WEA, whether it be informing the selection of a small area for initial or pilot-level development, or the design of a large-scale wind farm project filling a lease to near-full capacity.

Relaxing assumptions in our models did not change the spatial patterns detected nor the features of the spatial planning solutions found, indicating that our findings are relatively robust to nuances in how the sectors and their interactions are characterized. Our study was not comprehensive in its representation of each sector, however, or in representing all relevant sectors in the ecosystem. For example, while the groundfish fishery is far and away the highest value commercial fishery in the Morro Bay WEA, there is also fishing for highly migratory species like albacore tuna (Wang et al., 2022b). To the extent that this fishery has a different spatial pattern of value compared with the groundfish fishery, considering it could generate different optimal spatial plans of development than shown here. Furthermore, there are other sectors and ecosystem services beyond fisheries and wildlife conservation that can be impacted by wind farm development, including shipping industry, military, viewshed aesthetics, and the preservation of cultural value (Firestone et al., 2015; Lester et al., 2016; Lester et al., 2018c; Ten Brink and Dalton, 2018, CA-AB-525, 2021). In addition, our analysis is limited to impacts within the WEA, ignoring, for example, how transmission cable and support vessel routes to shore could impact fisheries access and benthic species (Maxwell et al., 2022). Finally, we focused on power production, while recognizing that the economic value of the power produced also is important to the energy industry (Wang et al., 2018). The Morro Bay WEA's deep waters and far distance from shore indicate a wind farm there would require unusually high capital and operational costs (Beiter et al., 2020). Accounting for these costs (e.g., via an estimate of levelized cost of energy, or average net present cost of power generation for a turbine over its lifetime), could reveal a more homogeneous spatial pattern of energy value across the WEA, compared with our estimate of energy value based on power production (Beiter et al., 2020). As such, the energy sector may gain less than we estimate here from development of the western sites farthest shore. Consideration of all of these additional factors would generate a more complete understanding of offshore wind farm impacts and spatial planning solutions for mitigating them.

An analysis based on static spatial data layers does not resolve dynamic responses to wind farm development, such as redistribution of fishing effort in response to fish stock build-up inside and spillover beyond the *de-facto* protected wind farm area (Smith and Wilen 2003; Abesamis and Russ 2005; Fayram and De Risi 2007; Harrison et al., 2012, Horta e Costa et al., 2013; Abesamis et al., 2014; Wilber et al., 2022); behavioral and demographic changes in marine wildlife affecting their population growth (Harwood et al., 2017; Horswill et al., 2017); and, more generally, changes in ecosystem function (Mangi 2013; Raghukumar et al., 2023). Ignoring these factors, as we did, could lead to inaccurate estimates of sector responses and poor guidelines on wind farm design for meeting the sector's objectives. However, a comparison of spatial planning analyses found the design of marine protected areas to be similar using static vs. dynamic models if fisheries were well managed (Brown et al., 2015), which is currently the case for the U.S. West Coast groundfish fishery (NOAA, 2024b). For seabirds, a decline in abundance due to direct mortality from turbines could be exacerbated by depensatory effects on the species' rate of survival and reproduction, impacting its population viability (Horswill et al., 2017). However, this dynamic response is not expected to vary spatially at the scale of our analysis, because the small size of the Morro Bay WEA relative to the foraging territory and migratory patterns of seabirds, and its location far from the coast, means that different patches in the WEA are similarly close to foraging and breeding sites throughout the CCE (and beyond) (Block et al., 2011). Thus, consideration of depensatory dynamics may not change the relative impact of development in a patch on seabird population vulnerability (highest in the west, lowest in the east), only that the overall impact be underestimated. For cetaceans, the greatest impact from wind farm development may be acoustic damage to individuals from turbine pile driving, which could be mitigated through dynamic management of construction operations over specific months of the year to not overlap with the presence of migratory whales (Best and Halpin 2019). However, pile driving is unnecessary for the type of deepwater, floating offshore wind farm considered here and thus should not affect the results presented here (Farr et al., 2017). Conservation gains may still be possible from dynamic management of the Morro Bay WEA in relation to seasonal distributional patterns of cetaceans, for example via regulation of schedules of support vessels to mitigate ship strikes (Southall et al., 2021; Stepanuk et al., 2022). However, the small relative difference in cetacean population vulnerability found across the Morro Bay WEA (<10% difference among the three leases) suggests that consideration of dynamic distributional patterns of these species will not alter the relative spatial impact of wind farm development.

Nonetheless, dynamic models are critical for evaluating processes expected to change over space and/or time, and they can reveal emergent ecosystem properties affecting, among other outcomes, spatial management (Halpern et al., 2013; White and Costello 2014; Sumaila et al., 2015; White 2023). Furthermore, the oceans are changing climatically and becoming increasingly crowded with human activities, affecting the ocean's response to environmental and anthropogenic pressures – and society's reaction to those responses – differently today versus in the future (McCauley et al., 2015; Dietz et al., 2021). Static models cannot capture these dynamics precisely, especially when they are driven by processes that cover a large spatial domain (e.g., long-distance marine larval dispersal) or need to be evaluated over an extended time horizon (e.g., decades-long) (Brown et al., 2015). In these cases, dynamic modeling is valuable for investigating and forecasting future outcomes of today's scenarios and decisions (Brown et al., 2015). One approach is for static models, such as this study and others (Theuerkauf et al., 2019; Morris et al., 2021; Riley et al., 2021; Rockwood et al., 2022; González Ortiz et al., 2023; Wickliffe et al., 2024), to provide an efficient "first cut" analysis that uses fewer resources to develop and analyze than a more complex dynamic model. Intriguing and consequential results, such as (found here) the ability to substantially mitigate the energy-fisheries tradeoff with spatial planning in relation to the hotspot and near-zero areas of fisheries value in the WEA, could then be explored further using dynamic models (White et al., 2012; Lester et al., 2018c).

A primary step in BOEM's offshore wind leasing process is to minimize impacts to existing ocean uses and the presence of natural and cultural resources through avoidance and mitigation procedures (BOEM, 2024a). We inform this process with a case study of the Morro Bay WEA, as well as provide an analytical framework that can be applied to the growing number of locations worldwide that may soon be developed for offshore renewable energy, aquaculture, and other emerging marine technologies (Gentry et al., 2017; Lester et al., 2018b; Weiss et al., 2018). The case study illustrates the spatially variable effect of wind farm development on energy and three major sectors of concern, and quantifies and compares the differential cumulative effect of development among three leases in the WEA on each sector. It also reveals high-energy, low-impact solutions or "seed" plans – in the form of maps of wind farm size, location, and configuration – that could be used to support evaluations and negotiations of wind farm development within each lease (de Groot et al., 2014; Haggett et al., 2020). The spatial models of the sectors also provide a foundation for the design of an empirical impact analysis in the WEA (Carey et al., 2020). The tradeoff analysis framework represents a highly-accessible analytical tool for leveraging the wealth of geospatial data and using it to support strategic, sustainable development of the seascape. In this era of unprecedented number of marine user groups and rapidly emerging rate of exploitation of ocean environments that are increasingly recognized as finite in area and resource supply (Perissi and Bardi, 2021), marine spatial planning with tradeoff analysis is essential for determining how and where the ocean will be used in a way that successfully balances society's objectives (Dundas et al., 2020; Wickliffe et al., 2024). Its value is further necessitated by the urgency to deploy renewable energy to stabilize the climate as quickly as possible (Lesk et al., 2022).

CRediT authorship contribution statement

Crow White: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Yi-Hi Wang:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ryan K. Walter:** Writing – review & editing, Visualization, Conceptualization. **Benjamin I. Ruttenberg:** Writing – review & editing, Conceptualization. **Danny Han:** Writing – review & editing, Data curation. **Eli Newman:** Writing – review & editing, Data curation. **Ethan R. Deyle:** Writing – review & editing, Conceptualization. **Sucharita Gopal:** Writing – review & editing, Conceptualization. **Les Kaufman:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2024.101005.

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