A PORPOISE-DRIVEN APPROACH: USING AGENT-BASED MODELS TO PREDICT POPULATION CONSEQUENCES OF OFFSHORE WIND NOISES ON GULF OF MAINE HARBOR PORPOISES

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ABSTRACT

A PORPOISE-DRIVEN APPROACH: USING AGENT-BASED MODELS TO PREDICT POPULATION CONSEQUENCES OF OFFSHORE WIND NOISES ON GULF OF MAINE HARBOR PORPOISES

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Marine mammals are increasingly exposed to anthropogenic noises, including from offshore wind activities, necessitating the development and refinement of tools to predict the effects of noise on their populations. Agent-based models (ABMs) are an effective tool that can simulate realistic movements and behaviors of animals to quantify population consequences of disturbance. In this study, I used the Europe-based ABM 'DEPONS' to (1) evaluate its effectiveness in a new environment, the Gulf of Maine, USA/Bay of Fundy, Canada, and (2) develop estimates of the population dynamics of local harbor porpoises (*Phocoena phocoena*) interacting with expected noises from proposed floating offshore wind farm construction and operation. This new, local formulation of the model produced realistic population dynamics through year eight, enabling preliminary estimates of population effects from reduced foraging success. Modeled porpoise movements appeared visually similar to those of real, satellite-tracked porpoises, but mean home range sizes and maximum net squared displacement differed significantly. Construction and operational noise, simulated separately, both caused minor population declines (0.019% and 0.59%, respectively). Operational noise effects started small and increased over time, whereas construction noise effects did not change

substantially over the impact period. Additional model calibration is needed, ideally based on more tracking data from GPS tags. Once calibrated further, the model can be used to estimate the cumulative impacts of a variety of noises on harbor porpoises near the Gulf of Maine/Bay of Fundy and inform management decisions.

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Finally, I dedicate this thesis to my late animal companion and friend through many dangers, Shadowfax.

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INTRODUCTION

Offshore wind (OSW) energy is a well-established, alternative energy source in regions like northern Europe and East Asia, yet emerging in others like the United States and Canada. While it has the potential to contribute to a reduction in US and Canadian emissions from power production, many unknowns still exist, including the full scope of potential effects on cetaceans (whales, dolphins, and porpoises). Of particular note is how noise generated by OSW turbine construction and operation, as well as by maintenance vessel traffic, influences the behavior of these organisms, and if those behavioral changes have population-level effects like declines in abundance or distribution shifts (Carstensen et al., 2006; Frankish et al., 2023; Graham et al., 2017; Holdman et al., 2023). Unfortunately, it is difficult to observe these fine-scale behavioral changes, and then extrapolate to assess their effects on population dynamics. Researchers have studied and continue to study noise-related impacts of turbine construction, operation, vessel traffic on harbor porpoises (*Phocoena phocoena*) in northern Europe, especially in the North Sea (Carstensen et al., 2006; Frankish et al., 2023; Graham et al., 2017; Nabe-Nielsen et al., 2018). Among these studies are ones that use agent-based models (ABMs) to evaluate how anthropogenic disturbances affect porpoise movement, feeding ecology, and energetics, and how this influences population health (Gallagher et al., 2021a; Nabe-Nielsen et al., 2018).

ABMs are sophisticated computer simulations that – among other applications – can replicate animal movements and responses to disturbances, and then quantify those effects at the population scale (Nabe-Nielsen et al., 2018). The technical qualities of ABMs are described further in the 'Agent-Based Models and DEPONS' section of the Literature Review. ABMs, such as the one used in this study, can be used in cumulative impact assessments and related population-level studies to estimate effects of existing or proposed marine developments in conjunction with baseline disturbances, like shipping traffic and fisheries bycatch. Cumulative impact assessments are required as a part of the U.S. Environmental Impact Assessments (EIA) process. However, to my knowledge, no such U.S.-based studies have used publicly available ABMs to estimate cumulative impacts of noise on marine mammals, creating demand for ABMs and other spatially-explicit population consequences of disturbance (PCoD) models for use in research, EIAs, and broader management efforts (Nabe-Nielsen et al., 2018; Pirotta et al., 2018). Given that the U.S. East Coast has three industry-scale operational offshore wind farms (OWFs), four under construction, and approximately 16 proposed with leases secured, plus four Canadian projects proposed off the coast of Nova Scotia, there is a need for predictive modeling studies to inform policy, regulations, and industry practices that can lead to ecologically sustainable outcomes.

In this study, I apply an existing North Sea-based ABM ('DEPONS') to a harbor porpoise population in the waters off the U.S. East Coast and Nova Scotia, Canada for two key reasons: (i) to test its suitability for local PCoD impact assessments and identify knowledge gaps that need to be addressed to obtain management-quality predictions, and (ii) to estimate how OWFs affect the harbor porpoise population in this region. Through use of local data, I reimplement this model to simulate various OWF and associated vessel-traffic scenarios in the western Atlantic Ocean for the Gulf of Maine/Bay of Fundy (GoM/BoF) porpoise population (NMFS, 2022). Because DEPONS has yet to be tested outside of the North Sea and Inner Danish Waters, the first goal is to evaluate its realism and how it functions in new environments. This, in turn, will inform the types of field data local scientists must collect to refine the model and get more robust estimates of the population-level effects. Because DEPONS is a mechanistic model, the mechanisms in theory should hold across regions, but they should, nonetheless, be tested and improved using local data. Ideally, through model testing, collection of additional local data, and re-parameterization, DEPONS can become a robust PCoD model for assessing cumulative impacts of U.S. and Canadian OSW developments on cetaceans, principally porpoises.

Harbor porpoises are an excellent focal species to study offshore wind noise impacts. First, there is considerable overlap of the GoM/BoF population and proposed OWFs (Holdman et al., 2023; Roberts et al., 2023; Jacobson, Bourdeau, Nabe-Nielsen, and Gallagher pers. comm., 2024). Moreover, the species is protected under the Marine Mammal Protection Act (MMPA), emphasizing the conservation importance of developing validated management tools. They are known to be vulnerable to anthropogenic impacts, including entanglement, pollution, and, most importantly to this study, noise disturbance (NMFS, 2025). Additionally, they are highly energetic and must maintain high foraging rates, suggesting that disturbances that produce deviations from normal foraging behavior may cause changes to individual survival and fitness (Rojano-Doñate et al., 2018; Wisniewska et al., 2016). They are also fast-lived (Read & Hohn, 1995), making population effects easier to observe over shorter periods than for longer-lived cetaceans. Finally, development of this ABM may also catalyze development of ABMs for other cetacean species of concern offshore from the U.S and Canadian coasts.

I choose to study the upcoming GoM OSW development in part because of the co-occurrence with the GoM/BoF porpoise population. GoM lease areas are located off the eastern coasts of Maine, New Hampshire, and Massachusetts (Figure 1). They range from 21.6 to 46.2 nautical miles (nm) from the nearest shoreline and lie above the outer continental shelf. On October 29, 2024, the U.S. Bureau of Ocean Energy Management (BOEM) concluded the auction of offshore wind lease areas in the GoM. Four of the eight outer continental shelf lease areas (OCS-A) received bids (BOEM lease block numbers OCS-A 0564, 0568, 0562, and 0567), totaling 439,096 acres (approximately 1,777 km^2) in epipelagic waters ranging from 120 to 200 m depth (BOEM, 2024). The state of Maine intends to construct a purpose-built port on Sears Island to stage all construction and maintenance support, including fabrication and turbine assembly (Office of Governor Janet T. Mills, 2024).

Turbines in the GoM lease areas must be floating due to the infeasibility of fixed-bottom turbines at depths greater than approximately 60 m (Musial et al., 2024; Risch et al., 2023). As such, construction will not involve pile driving, which can generate louder, impulsive noises than construction vessels (Frankish et al., 2023; Gall, 2021; Tougaard et al., 2022). Instead, a series of vessels will install anchors at each turbine location, connect mooring lines to each anchor, tow each turbine to its respective location, attach it to the mooring lines, and connect it to transmission infrastructure (likely a buried transmission cable; Jacobson pers. comm., 2024). Described in greater detail in the ‘Scenario Descriptions’ of the Methods section, ships typically produce lower amplitude noise than pile driving, but sound is sustained for longer periods of time (Frankish et al., 2023; Gall, 2021; Tougaard et al., 2022).

Leaseholders are entitled to survey these areas, develop designs and construction plans for their floating offshore wind (FOSW) facilities, and eventually apply for permits. If approved, construction may begin within 8 years or less, subject to delays from permitting issues or political headwinds (Kearns & West, 2018). This short impact assessment timeline emphasizes the need for sound methods, including predictive models like ABMs, to estimate population-level effects of OSW construction, operation, and maintenance on local marine mammals. Findings can inform permitting decisions, construction schedules (Nabe-Nielsen et al., 2018), best management practices (Dähne et al., 2017), turbine design (May et al., 2020; Stöber & Thomsen, 2021; Tougaard et al., 2020), and post-construction monitoring activities to mitigate impacts of future developments (Holdman et al., 2023; Niemi & Tanttu, 2020).

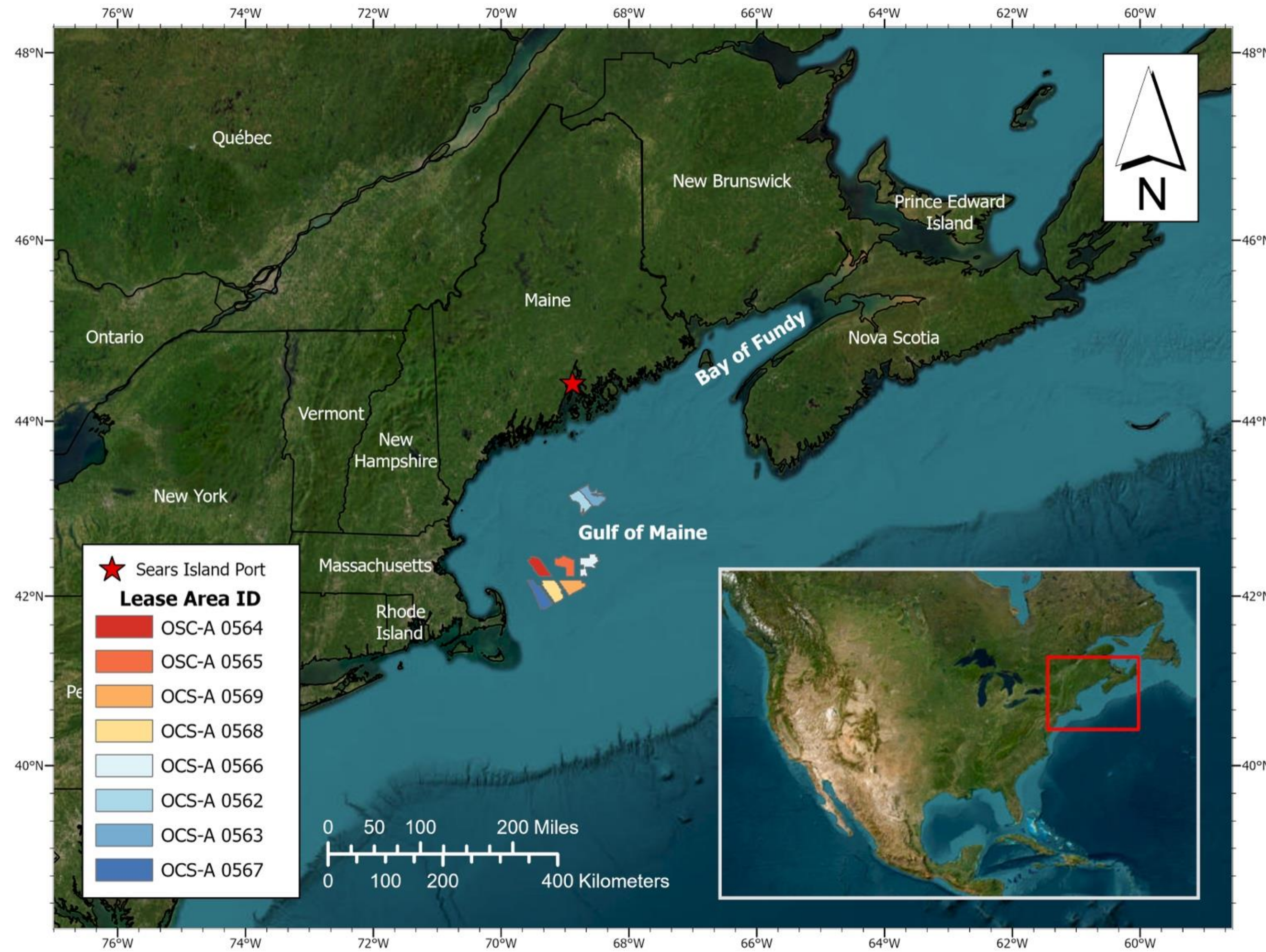

Figure 1. Study Area based in the Gulf of Maine, United States and Bay of Fundy, Canada. The main map shows the study area extent used in the DEPONS simulations, represented by the red box in the inset map. The red star denotes the location for the proposed Sears Island Port, the planned location for OSW turbine assembly, deployment, and maintenance staging. Four lease areas (OCS-A 0564, 0568, 0562, and 0567) have been leased, while the other four are currently not planned for development (BOEM, 2024).

Literature Review

Distribution and Habitat

Harbor porpoises are widespread throughout the coastal temperate, subarctic, and arctic waters of the Northern Hemisphere (National Oceanic and Atmospheric Administration [NOAA], 2024). True to their name, they frequently inhabit coastal waters within 10 kilometers (6.2 miles) of shore (Allen et al., 2011) but are also found hundreds of kilometers from shore (Gilles et al., 2016; Roberts et al., 2023). The species generally resides in waters less than 150 or 200 m deep, including estuaries, inlets, and open ocean habitats (NMFS, 2022; Roberts et al., 2023). Genetic analyses identified four porpoise populations in western Atlantic waters: the Gulf of Maine/Bay of Fundy, Gulf of St. Lawrence, Newfoundland, and Greenland populations (Hayes et al., 2022). The GoM/BoF population is present in areas of current and proposed offshore wind development in the Gulf of Maine.

The GoM/BoF population has a spatially extensive and temporally dynamic distribution along the US and Canadian eastern coasts. The population ranges from North Carolina, United States (approximately 35°N) north to the Bay of Fundy (approximately 46°N) (NMFS, 2022; Roberts et al., 2023). Porpoises are especially abundant during the summer in and around the northern GoM, southern BoF and around the southern tip of Nova Scotia (NMFS, 2022; Holdman et al., 2023; Roberts et al., 2023). Interestingly, passive acoustic monitoring in southern New England waters near Martha’s Vineyard observed a near absence of porpoises from June to December (Van Parijs et al., 2023).

This suggests a strong range restriction to the GoM and BoF until winter. In winter, some porpoises perform unsynchronized, seasonal southward movements (i.e., not a coordinated migration), increasing densities along coastlines from New Jersey to North Carolina (Read and Westgate, 1997; Wingfield et al., 2017). However, even during this time, populations remain most abundant in the GoM and the greater New England area (Roberts et al., 2023).

Life History and Natural History

Porpoises are relatively short-lived, small, elusive, coastal and epipelagic, piscivorous odontocetes (toothed whales) with high energy demands that typically hunt in very small groups (Gilles et al., 2016; Read & Hohn, 1995; Rojano-Doñate et al., 2018; Sveegaard et al., 2012; Wisniewska et al., 2016). They are capable of living past 20 years in the wild, though most do not live past ten (Learmonth et al., 2014; Read & Hohn, 1995). The oldest individual observed from the GoM/BoF population (captured through fisheries bycatch) was 17 years old (Read & Hohn, 1995). Though they are often considered top predators in some habitats, their small size makes them occasional targets for larger marine megafauna like bottlenose dolphins, orcas, white sharks, and gray seals, with the latter three occasionally eating killed porpoises (Bouveroux et al., 2014; Gallagher et al., 2021a; Giles et al., 2024; Gilles et al., 2016; Ross & Wilson, 1996).

Maintaining high foraging rates is especially vital for porpoises, and losses of these opportunities can directly affect survival (Gallagher et al., 2021b; Nabe-Nielsen et al., 2018; Wisniewska et al., 2016). Individuals are small for a cetacean (total length = 147-158 cm as adults, varying by population), meaning they have a high surface-area-tovolume ratio leading to greater heat loss compared to larger cetaceans (Learmonth et al., 2014; Rojano-Doñate et al., 2018). They also reside in cool waters and have thinner blubber layers than other cetaceans (Rojano-Doñate et al., 2018). These attributes require porpoises to forage at high rates to maintain the appropriate body heat and meet their metabolic demands to survive (Read & Hohn, 1995; Rojano-Doñate et al., 2018; Wisniewska et al., 2016). Recent studies estimate foraging rates from anywhere between 20-53% of the time (Holdman et al., 2023), to > 60% (Rojano-Doñate et al., 2018), to “nearly continuously” (Wisniewska et al., 2016), though the latter observation took place in Danish waters where preferred larger prey have disappeared. In the GoM/BoF, they primarily hunt and consume hundreds of small schooling fish (<25 cm, commonly 3-10 cm) per day, with GoM/BoF individuals depending largely on Atlantic herring, as well as silver hake during the summer months (Palka et al., 1995). Assessments of porpoise diet in other regions found the species can consume prey up to 35.5 cm in length, though prey modal lengths are 11 cm or less, suggesting foraging plasticity (Santos et al., 2004). Larger prey are more energy dense per fish, suggesting that the switch to smaller prey may be due to environmental changes, like climate change, overfishing of larger fish, and the increase in Atlantic herring biomass since the mid-1970s (Gallagher et al., 2021a; Read & Gaskin, 1990). It also uses less energy to pursue smaller prey, but this strategy is at least somewhat dependent on access to schools of fish or prey aggregating along fronts (Rojano-Doñate et al., 2018). Given their need to feed often to maintain their energy balance, porpoise populations may decline if foraging rates drop as a result of exclusion, even temporarily, from suitable feeding areas (Nabe-Nielsen et al., 2018).

Each porpoise population varies in life history traits, including population growth rates and morphology. Most estimates of the current population growth rates for the GoM/BoF population vary from approximately 4% to 9.4% depending on the study and methods used, with Monte Carlo simulations producing a 90% confidence interval of a 3-15% annual growth rate (Barlow & Boveng, 1991; Caswell et al., 1998; Moore & Read, 2008; Woodley & Read, 1991). This suggests the population is below carrying capacity, which is determined by prey availability, life history traits, and anthropogenic disturbances, among other forces. Moore & Read (2008) used a Bayesian framework to estimate annual growth rate in the absence of bycatch mortality, yielding a median posterior estimate of 4.6%. The National Marine Fisheries Service (NMFS) finds this to be the most dependable estimate with minimal uncertainties (NMFS, 2022). The population's mean age at sexual maturity/first reproduction is 3.36 ± 0.13 years, after which they typically reproduce annually (Read, 1990; Read & Hohn, 1995). The gestation period is approximately 10.6 months, and lactation lasts 8 to 12 months (Read & Hohn, 1995; Palka et al., 1995). Mean calf length varies between 93 ± 8.2 cm (measured in August) and 108 ± 2.0 cm (measured between June 1 and September 30), while adult asymptotic length is 155 cm for females and 144 cm for males (Read, 2001; Read & Hohn, 1995). Adults grow to their asymptotic length in approximately three to four years, with males reaching this length a year or two before females (Stepien et al., 2023). Mean calf mass at weaning is 26.8 ± 1.21 kg (Read & Hohn, 1995) and adult mass can reach 90 kg (Allen et al., 2011). All of these local values vary from the metrics observed elsewhere in the Atlantic Ocean and beyond.

Population Status and Threats

The GoM/BoF population boasts an estimated abundance of 95,543 individuals (coefficient of variation = 0.31), with a minimum population size of 74,034 (NMFS, 2022). These estimates sum the 2016 Northeast Fisheries Science Center and the Department of Fisheries and Oceans Canada surveys, which cover different areas within the population's range. The species is classified as MMPA Protected, prohibiting "take" of any individuals, including but not limited to hunting, harassing, capturing, or killing, except when authorized through a NMFS permit (Marine Mammal Protection Act of 1972). Porpoises are not otherwise granted conservation status in the United States, though they are listed as a threatened species in Canada (NMFS, 2022).

Harbor porpoises are under threat principally from fishing gear entanglement, noise pollution, prey declines, and contaminant exposure, though vessel strikes are worth monitoring as well (NMFS, 2022; Stokholm et al., 2025). In the GoM, the gillnet and bottom trawl fisheries are the most common sources of porpoise entanglements (Caswell et al., 1998; NMFS, 2022). An estimated average 163 GoM/BoF porpoises per year die to commercial fishery bycatch, though this is a known undercount primarily due to poor and inconsistent observer coverage (NMFS, 2022). Fishery-related mortality and serious injury are large enough (i.e., greater than 10% of the Potential Biological Removal value of 851 porpoises) that such impacts cannot be considered insignificant to the population (NMFS, 2022). While vessel strikes do occur, they are far less common for porpoises than slower baleen whales (NMFS, 2022). Additionally, climate change is causing range shifts, population declines, and size changes in diverse taxa, which may include the prey fish of porpoises (Gallagher et al., 2021a; NMFS, 2022). Future studies may observe changes to porpoise distribution, behavior, and fitness because of these shifts in their prey. Finally, discussed further in this study, porpoises are frequently exposed to anthropogenic noise pollution, which can cause stress, harm to auditory organs, and shifts in behavior (Nabe-Nielsen et al., 2018; NMFS, 2022).

Bioacoustics and Noise Disturbance

Sound reception is an incredibly useful and commonly used sense for many marine animals, like porpoises (Au, 2000). Light diffuses quickly in the ocean, making vision less effective. Further, sound propagates farther and faster in water than air, often providing more information than other senses (Au, 2020; Erbe & Vigness-Raposa, 2022). As such, numerous species of diverse taxa, from baleen whales to coral planula larva, have well-developed sound detection (and often sound production) mechanisms, using acoustics as a fundamental sensory and communication pathway (Au, 2020; Budelmann, 1992; Prosnier, 2024; Vermeij et al., 2010; Wahlberg & Westerberg, 2005). Cetaceans depend heavily on their hearing to perform a variety of necessary functions. Whereas baleen whales, like humpback whales, primarily produce low-frequency sonar to communicate great distances with conspecifics, odontocetes like porpoises produce high-frequency sounds that enable them to echolocate, as well as communicate (Au, 2020).

Odontocetes produce high frequency ‘clicks’ and ‘buzzes’ to navigate and find prey (Gall et al., 2021). These are generated through a series of muscles, air sacs, and connective tissue in the nasal passages and directed through a bulbous, fluid-filled organ called the melon located in their forehead (Au, 2020; Reidenberg & Laitman, 2018).

These clicks then travel through the water and reflect off terrain and creatures. An individual's ability to hear the returning sounds allows them to sense their surroundings, navigate, and forage effectively in often dark or turbid environments. Harbor porpoises have a hearing range suited to the very high frequency clicks they make (peak frequency 120–130 kHz; Møhl and Andersen, 1973). They typically hear noises between 0.125 and 150 kHz, with their greatest sensitivity from 16 to ~140 kHz (Kastelein et al., 2017). Different species have their own hearing ranges, defined by the frequencies they are capable of hearing (Tougaard & Beedholm, 2019).

Cetaceans can experience behavioral and physiological changes if audible noises dramatically exceed normal noise levels (Frankish et al., 2023; Gall, 2021; Graham et al., 2017; Tougaard et al., 2022). Responses vary considerably depending on the affected species, the noise, and the environment. To trigger a behavioral response or cause physiological damage, noises must exceed certain sound pressure level (SPL, i.e., sound 'loudness') thresholds and be of a frequency the species can hear (Tougaard et al., 2022; Center for Marine Acoustics, 2023). The amount of time an organism is exposed to noise disturbance can also influence the level of disturbance (Tougaard & Beedholm, 2019). To constitute behavioral harassment and elicit a reaction in a porpoise, continuous sounds typically must reach 120 decibels (dB) relative to a reference pressure of one micro-Pascal (re 1 μPa), and multiple impulsive sounds must reach 160 dB re 1 μPa (Center for Marine Acoustics, 2023). These values are based on a sample of lab- and field-measured individuals and may vary by environment and individual. Reactions to behavioral harassment include fleeing, increased stress responses, changed dive behavior, and increased effort to overcome masking (Center for Marine Acoustics, 2023; Frankish et al., 2023; Rojano-Doñate et al., 2024; Stöber & Thomsen, 2021). Masking is when noises are loud enough and at the same frequency to cover up a marine mammal's ability to hear a signal (Thomsen et al., 2006). Loud noises may thus cause marine mammals to forgo communication and echolocation or exert additional energy to increase the amplitude of their sound signal, potentially altering natural foraging behavior and displacing marine mammals from otherwise favorable habitats (Thomsen et al., 2006). Porpoises experience auditory injury, including temporary hearing threshold shifts, when impulsive sounds exceed approximately 194 dB re 1 μPa (Lucke et al., 2008). All values reported are unweighted, root-mean-square SPLs.

Note that underwater SPL (dB re 1 μPa) is quantified and described differently than for sounds traveling through air (dB re 20 μPa; Larsen & Radford, 2018). This is due to (1) numerous differences in how sound behaves in each medium (e.g., attenuation, scattering, spreading, or interactions with boundaries), and (2) the use of different arbitrary reference pressures (1 μPa vs. 20 μPa). While not a perfect conversion method, one can subtract 61.5 dB from an underwater sound to estimate its SPL in air (Finfer et al., 2008). This conversion has limitations, but is useful for putting underwater sound levels into perspective.

Threshold SPLs for behavioral disturbance can vary by location because populations may be accustomed to the ambient noise levels of their habitat (Van Parijs et al., 2023). For example, porpoises can, but do not always, inhabit noisy environments like areas with high ship traffic and heavily-modified estuaries with historically high noise levels (Taupp, 2022). Passive acoustic monitoring conducted off the coast of Long Island, New York and southern Massachusetts, United States (within the southern extent of the study area) measured median broadband SPLs between 105 to 112 dB re 1 μPa (Van Parijs et al., 2023). Broadband noises were on average quieter in the higher frequencies that porpoises are capable of hearing.

Anthropogenic noise is becoming increasingly common in the ocean as marine activities like shipping, fishing, oil and gas exploration, and offshore wind energy development expand. To have an impact on a marine mammal, these noises must fall within a species' hearing range and be loud enough to cause a physiological or behavioral impact. If and when an individual impact occurs, and depending on the spatial and temporal scale of the impact, there may be an effect on the population. Table 1 describes some common anthropogenic noises in the marine environment and summarizes the observed effects from studies reviewed.

Table 1. Representative characteristics of some common types of anthropogenic marine noise. Frequency describes the pitch of the noise and thus determines if a species can hear it. Note that underwater and airborne noise are measured differently (dB re 1 µPa vs. dB re 20 µPa) and thus cannot be compared directly. Sources: [1] Bellman et al. (2023); [2] Tougaard et al. (2020); [3] Center for Marine Acoustics (2023).

Sound Source	Frequency (Hz)	Mean Sound Pressure Level (dB re 1 µPa)
OSW Turbine Operation (3.6 - 8.4 MW nameplate capacity)	Low (25 - 400)[1,2]	120[1,2]
OSW Pile Driving	Medium (<2000)[3]	221[3]
Seismic Airgun Surveying (Oil & Gas)	Low (10-200)[3]	~250[3]
Large Vessel Traffic (e.g. shipping vessel)	Low to Medium (<1000)[3]	160-180[3]
Small Commercial Fishing Vessel	Medium to High (500-10,000)[3]	<165[3]

Porpoise responses to these noises may be as variable as the noises themselves. Studies have observed harbor porpoise presence and residence time decrease near OSW turbine pile driving, potentially preventing access to suitable prey (Carstensen et al., 2006; Stokholm et al., 2025), with effects extending up to 25 km from the piling (Dähne et al., 2017). Displacement effects are temporary, with porpoises often returning near impact sites between six hours and three days (Stokholm et al., 2025). Avoidance behaviors have been observed to varying degrees with both impact and vibratory pile driving (Graham et al., 2017). On occasion, pile driving has little-to-no effect on probability of porpoise occurrence in and away from the construction area (Graham et al., 2017), though this is rare. Bubble curtains – barriers of bubbles deployed around pilings – can reduce piling noise substantially (by 7-12 dB re 1 µPa), reducing the impact zone to

12 km (Dähne et al, 2017). Harbor porpoises are also sensitive to ship noise (Center for Marine Acoustics, 2023; Frankish et al., 2023; Tougaard et al., 2020). Porpoises will often swim away from a ship or dive deeper to avoid ship noises, and may be behaviorally affected more than 2 km away (Frankish et al., 2023). Less is known about porpoise response to wind turbine operational noises, which are typically 10-20 dB re 1 μPa quieter than ships at the same frequency (Tougaard et al., 2020).

Operational turbines exhibit a mean SPL of 120 dB re 1 μPa (for current, smaller turbines; Tougaard et al., 2020) to 170 dB re 1 μPa (for a modeled 10 MW turbine; Stöber & Thomsen, 2021). Of note to this study, operational noises are generally below 1 kHz, though they may include strong tonal elements associated with the gear box mechanism located in the turbine nacelle (Pangerc et al, 2016; Tougaard et al., 2020). These tonal elements are presumed absent in newer direct drive turbines, which are becoming increasingly preferred and deployed (Tougaard et al., 2020). Direct drive turbines are also on average 10 dB re 1 μPa quieter than those with a gear box (Stöber & Thomsen, 2021). The few published peer-reviewed studies on porpoise behavior from operational noise have documented variable effects. Risch et al. (2023) observed reduced residence times in very small radii around turbines, while Scheidat et al. (2011) observed increased abundance in the wind farm area, possibly due to increased fish presence and less ship-borne sound. Teilmann and Carstensen (2012) detected reduced echolocation activity in wind farm areas post-construction, but also a slow, progressive return of echolocation activity over ten years. This suggests that porpoises are deterred from wind farms because of construction noise and that they may gradually acclimate to operational noise. However, these findings vary greatly by local environmental noise conditions (e.g., wind speed) and baseline anthropogenic noise.

Turbines are also getting larger (and therefore higher in generation capacity), and most wind farms studied are fixed-bottom, not floating like those proposed for the GoM. Larger turbines typically are louder (Baldachini et al., 2024; Stöber & Thomsen, 2021; Tougaard et al., 2020), but simultaneously require fewer turbines to generate the same amount of electricity (Stöber & Thomsen, 2021). Marmo et al. (2024) observed similar sound profiles for floating and fixed-bottom turbines at 100 m distance from the turbines. The findings from Burns et al. (2022) concur, observing continuous noise frequencies below 500 Hz. However, they also detected brief (~1.5-s) tonal noises from the mooring systems close to the floating hull. This suggests the tonal noises will not occur along the deeper extents of the mooring lines (Burns et al., 2022). The body of literature on floating turbine noise is small and largely composed of white papers, and will require further study.

Agent-Based Models and DEPONS

An ABM is a computer simulation model where adaptive agents (e.g., animals) move and interact with each other and their environment based on specified rules (i.e., algorithms that are shaped by parameters), allowing higher-level or large-scale phenomena (population dynamics, distributions, etc.) to emerge (Grimm et al., 2005). ABMs (also called ‘individual-based models’) are used to study a variety of phenomena, from disease spread (Chiacchio et al., 2014) to electric vehicle charger usage (Sheppard et al., 2016) to animal behavior (Chudzinska et al., 2021; Gallagher et al., 2021a; Nabe-

Nielsen et al., 2018; Stillman et al., 2015). When used in an ecological setting, an ABM can link the behavior of individual animals to the state of its population, such as through competition for a limited resource (Stillman et al., 2015). By incorporating the real-world behaviors of individuals into the model (e.g., how an organism flees from a disturbance, or how it moves when hungry vs. satiated), it can simulate an entire population, offering insights to how it functions under normal and impacted conditions.

ABMs are well-suited for the study system and the goal of estimating the population-level impacts to porpoises where other methods are insufficient or onerous. Cetaceans are difficult to observe, and traditional methods like field studies, lab experiments, and frequentist models are often insufficient in translating effects on individuals into population consequences (Grimm et al., 2005; Stillman et al., 2015). Furthermore, an ocean study system is laborious, complicated, and costly to survey, and even other technology-based tools like acoustic monitoring and GPS tracking can be expensive and require permitting. If parameterized using robust local data, an ABM like DEPONS can properly simulate individual behavior, not only in a controlled environment, but in response to a hypothetical disturbance. Being able to accurately simulate these behaviors is especially important for animals, like porpoises, that are presumably sensitive to being scared away from their foraging grounds or losing foraging time (Gall et al., 2021; Wisniewska et al., 2016). Acute or prolonged noise disturbances have the potential to displace porpoises through avoidance and inhibit hearing, which is detrimental to their ability to locate prey (Nabe-Nielsen et al., 2018). It is imperative to know if porpoises will avoid foraging grounds due to OSW-related noise disturbances, if that avoidance will lead to reduced energy levels and reproductive success, and if those declines in fitness will translate to population declines.

DEPONS is an ABM that simulates the population dynamics stemming from intraspecific competition for a dynamically replenishing food resource, as well as from altered movements and reduced foraging success from noise disturbances. The documentation of DEPONS v3.2 is provided in a TRACE (TRAnsparent and Comprehensive model Evaluation) document that contains a comprehensive description of model inputs and functionality (https://github.com/jacobnabe/DEPONS/releases; Nabe-Nielsen et al., 2014). I summarize core components and mechanisms of DEPONS below.

This study is most concerned with three types of agents present in the model: porpoises, wind turbines, and ships. Each porpoise agent is a super individual, representing multiple real-world female porpoises and their dependent calves. Males are not included in DEPONS because the number of males is not considered a limiting factor on reproduction (Nabe-Nielsen et al. 2014). I therefore assume the number of males does not affect population dynamics. Porpoise agents are characterized by their location, direction, movement mode (large-scale [transient] or fine-scale [area-restricted]), speed, current energy level, age, pregnancy status, and lactating status. Ship agents are characterized by their location, speed, length, type, and SPL at 1 m. Length, type, and speed determine the noise source level for vessels based on MacGillivray and de Jong (2021). Wind turbine agents are characterized by their location, SPL at 1 m, and the start and end times of their noises. In the past, turbine agents have only been used to simulate pile driving noise (Nabe-Nielsen et al., 2018), but in this study, I reimplement them to simulate operational noise.

DEPONS is built around the assumption that porpoises must feed or search for prey near continuously to maintain sufficient energy levels and survive (Gallagher et al., 2021a; Nabe-Nielsen et al., 2018; Rojano-Doñate et al., 2018; Sveegaard et al., 2012; Wisniewska et al., 2016). In DEPONS 3.2, each porpoise agent's energy level is scaled to lie in the range 0-20 (unitless). It increases when an agent reaches and consumes a food patch and decreases as the agent moves. The energy obtained from a patch is dependent upon spatially explicit prey fields. Because data on prey density are limited, DEPONS studies typically use porpoise density as a proxy for food availability. This is based on the assumption that density distributions of porpoises and other highly energetic marine mammals are likely to be tightly correlated with the density distributions of their prey (Gilles et al., 2016; Nabe-Nielsen et al., 2014; Robinson et al., 2012). Agents with three consecutive days of decreased energy initiate large-scale movements and seek out more distant areas in search of energy (food patches). Lower energy levels increase an agent's probability of mortality or abandoning a lactating calf.

Another key way DEPONS achieves realistic movements is through the incorporation of spatial memory for fine-scale movements and persistent spatial memory (PSM) for large-scale movements (Nabe-Nielsen et al., 2014; Nabe-Nielsen et al., 2018). Real-world tracks in the waters off Denmark show that porpoises possess the ability to navigate back to prey patches, including places they have not visited for weeks or months (Berger-Tal & Bar-David, 2015; Nabe-Nielsen et al., 2014; van Beest et al., 2018). van

Beest et al. (2018) observed those porpoises moving long distances to forage in particular areas, suggesting that these areas may help them maximize food intake, though this cannot be verified. In the same way, DEPONS' large-scale movement mode enables animals to move towards optimal foraging areas that maximize energy intake and minimize distance traveled (and therefore, energy expended), a behavior observed in several other species (Austin et al. 2004; Fagan et al. 2013). While fine-scale spatial memory is guided by recently visited food patches and decays with time, PSM in large-scale movements is passed on to the calves of agents and does not decay. These components of movement ecology enable realistic movements that lend credibility to the emergent population dynamics observed (Nabe-Nielsen et al., 2014; Nabe-Nielsen et al., 2018; Stillman et al., 2015).

Upon experiencing a sufficiently loud turbine- or vessel-borne noise beyond a literature-defined threshold, a porpoise agent's movement will change. DEPONS uses a couple different sound propagation/attenuation models (the inverse squares law for turbine noise, and the Weston flux integral method [Weston, 1959] for ships) to accurately determine, at each time step, if porpoise agents are close enough to a sound source to hear a noise that exceeds their threshold. Porpoise agent movements are biased away from (i.e., the opposite direction of) the disturbance. The strength of the negative bias is related to their distance to the source. A nearby noise source will influence the direction of the agent's next movement more than a distant noise disturbance will, consistent with studies on real-world porpoise densities around a Dutch wind farm (Williamson et al., 2016). This disturbance-based bias is combined with influences from spatial memory and a correlated random walk to determine the direction an agent moves. Correlated random walk, only used in fine-scale movements, enables porpoise agents to move random directions at each time step, but turn angles are informed by the most recently moved direction. This generates more realistic movement patterns (van Beest et al., 2018).

METHODS

To estimate the emergent population dynamics of GoM/BoF porpoises in DEPONS, I first created the GoM/BoF environment in DEPONS using maps of local conditions. Then, I generated the disturbing agents in the form of baseline (i.e., non-OSW) vessels, OSW construction vessels, and operating turbines. Once the model was functional, I ran numerous simulations and inspected the emergent population dynamics, including any shifts due to noise disturbance. Finally, I more thoroughly evaluated the realism of the modeled population's movements to ensure that reasonable inferences could be made and identify areas of improvement for the model.

Study Area

The study area (Figure 2) encompasses the core habitat of the GoM/BoF harbor porpoise population (NMFS, 2022; Read & Hohn, 1995; Read & Westgate, 1997) and the proposed GoM offshore wind developments (BOEM, 2024). The GoM lease area footprint occupies water depths of approximately 120 to 200 m, approximately 21.6 to 29.5 nm off the coast of Massachusetts, USA at their closest edges. No other OSW developments have been proposed within the study area as of December 2025. I simulate this study area in the ABM, DEPONS.

Base Model Inputs

Previous studies have used DEPONS exclusively to simulate northern European waters, like the North Sea and Inner Danish Waters (Nabe-Nielsen et al., 2018; Nabe-Nielsen 2021). To simulate GoM/BoF porpoises in the study area, I used geospatial data to create the landscape, including local maps of environmental variables porpoises appear to be influenced by in Europe, like salinity and water depth (van Beest et al., 2018). I then updated life history parameter values for the local population to further add realism to agent behavior.

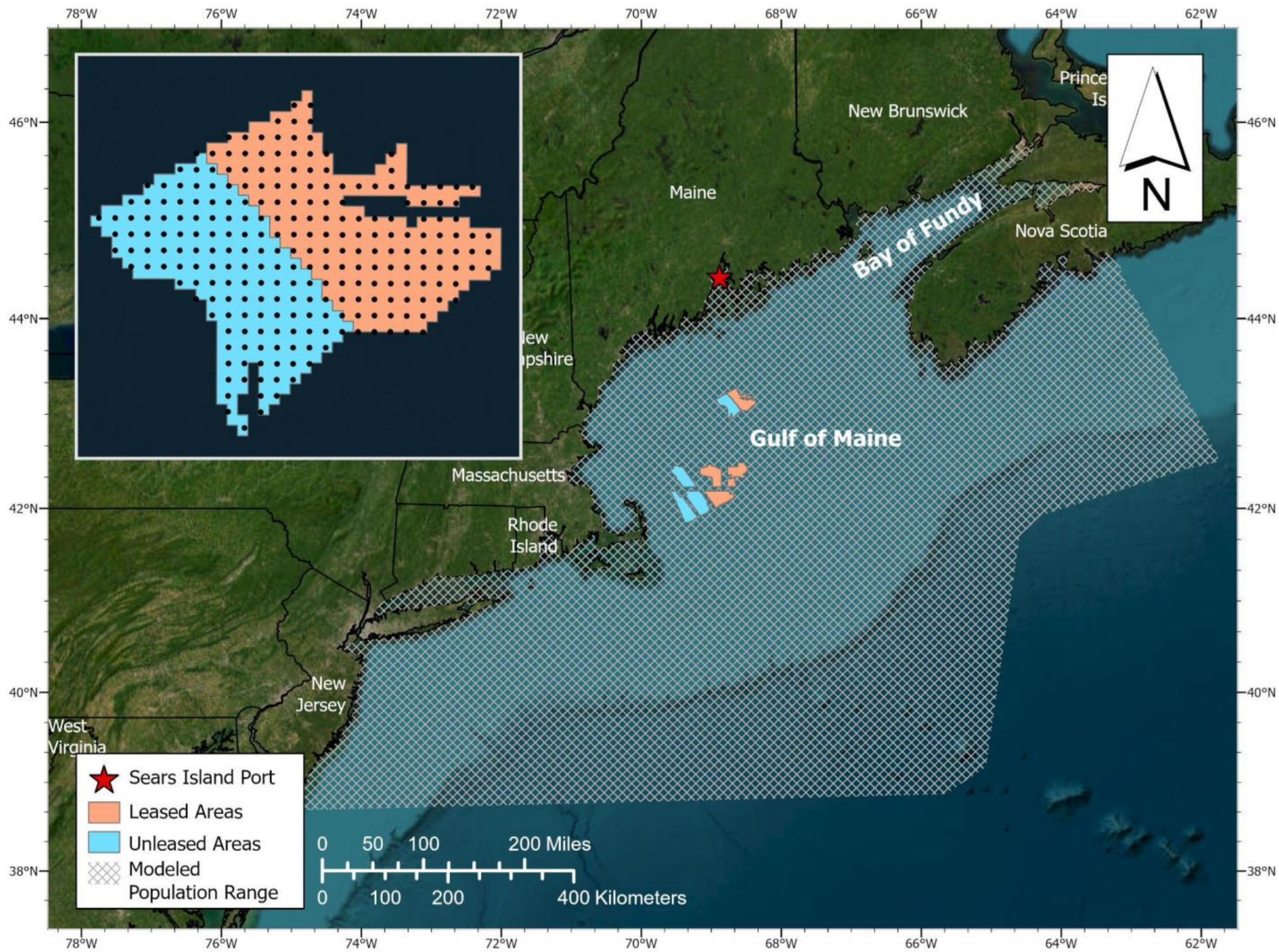

Figure 2. Extent of the Modeled Area. The gray checkered region shows the area modeled in DEPONS. Four of the eight lease areas (OCS-A 0564, 0568, 0562, and 0567) have been leased by developers (orange polygons). As of December 2025, there are no publicized plans to reopen the other four lease areas (blue polygons) for auction. The inset map shows an example of the turbine layout at 1-nm spacing, with turbines shown as black points. Basemap credits: Earthstar Geographics.

Landscape Setup

DEPONS requires seven types of maps to create the virtual spatial landscape that the agents interact with (Table 2). The landscape is generated through a combination of bathymetry, distance to shore, prey density (monthly), sea surface salinity (monthly), sediment size, “patches,” and “blocks” maps (patches and block maps are described below). A summary of maps and their sources is provided in Table 2, and a full description of the maps is provided in the DEPONS v3.2 TRACE. Maps are represented using a 400-m x 400-m grid in a UTM-based system; any maps not already at this resolution are resampled to it. Maps with finer resolution are preferred, where possible, to minimize upsampling and avoid the need for spatial interpolation. This study uses the projected coordinate system NAD 1983 Zone 19N (EPSG 26919). All externally sourced data used in this study are publicly available (Table 2). The blocks, patches, and sediment size maps are generated in R Version 2024.12.0+467 (R Core Team, 2024) for this landscape specifically.

Table 2. Summary of externally sourced maps used to generate the Gulf of Maine/Bay of Fundy landscape in DEPONS. DEPONS requires seven maps to simulate a landscape: bathymetry, distance to shore, prey density (monthly), sea surface salinity (monthly), sediment grain size, food patch locations, and blocks (i.e., user defined areas of interest). The latter three are created internally and therefore omitted from Table 2.

Map Type	Resolution	Source	Notes
Bathymetry	15 arc-seconds (approx. 420 m)	GEBCO, 2021	
Distance to Shore	0.01-degree (approx. 1.1 km)	OBPG, 2009	
Prey (monthly)	5 km	Roberts et al., 2023	Prey density data are unavailable, but porpoise distribution maps work as an effective proxy (see ‘Agent-Based Models and DEPONS’ section of Literature Review). Regions with absent data were temporally interpolated (see ‘Prey Map Transformations’ section of Methods)
Sea Surface Salinity (monthly)	1/12th-degree (approx. 5 km)	CMEMS, 2024	

Notes: Maps used are the highest resolution maps found for the Gulf of Maine/Bay of Fundy region.

The “blocks” map identifies user-determined grid cells of interest to facilitate analyses of smaller areas of interest. These can include areas surrounding wind farms or important habitats. Blocks generated for this study use a 10-km buffer around wind turbines to examine changes at more local scales. This is based on Stöber and Thomsen’s (2021) model estimate that a marine mammal would experience behavioral disturbance (i.e., NOAA Level B harassment) up to 6.3 km from a single 10 MW gearbox turbine. This study uses 10 km because it conservatively represents an increased maximum disturbance distance for a 15 MW turbine, given that larger turbines typically produce more noise (Tougaard et al., 2020).

Because median sediment grain size can affect sound propagation for ships in DEPONS, the model uses a sediment map to influence the movement of sound through simulated space. While some local data exist, they contain a high number of missing data points, which makes interpolation highly variable and unreliable. Instead, I created a uniform map with a sediment grain size value of 2.6, which is near the median grain size in the North Sea and is fairly consistent with the grain size of the GoM's sandy clay seafloor (Dickson & Jacoby, 2012). Future studies can refine this value or use maps of sediment size distribution.

Finally, the "patches" map describes the location of prey (food) patches. Patches are randomly distributed throughout the study area, with prey cells occupying 1.6% of the water cells in the grid. This frequency, while arbitrary, is sufficiently large to result in realistic movements in the North Sea (Nabe-Nielsen et al., 2013; 2014). The maximum amount of food found in each patch in a given month is obtained from the corresponding monthly prey map.

Prey Map Transformations. I used monthly modeled porpoise density maps from the Duke Marine Geospatial Ecology Lab (MGEL) as a proxy for prey density (Roberts et al., 2023) because local prey distribution data are unavailable. These MGEL maps are based on extensive aerial and shipboard surveys conducted from 1998-2020 during calm, high visibility conditions (i.e., sea states of Beaufort 2 or less). Due to poor survey conditions, the most northern extents of my study area (the inner extent of the Bay of Fundy and the waters off of the southeastern coast of Nova Scotia) are not included in MGEL's December-May maps. To fill in these gaps, I conducted temporal interpolation (specifically, trigonometric interpolation using sine and cosine curves) on the missing areas, making inferences about the monthly porpoise densities in the six missing months based on the six months of available data (June-November). Trigonometric interpolation assumes raster cells of porpoise density follow a cyclical fluctuating pattern represented by a sine curve. Using the interpolate.maps function of the DEPONS2R package Version 1.2.7 (Nabe-Nielsen et al., 2025) in R, I fit this curve to the existing data to infer the porpoise densities in the missing months. The resulting interpolated areas showed unrealistically high porpoise densities because the training data were from summer months, when porpoises are most abundant near Nova Scotia. So, I then scaled down the interpolated area to match the maximum of the southern extent in each month. This produced smoother-looking density distribution maps without stark differences between the interpolated and unaltered areas.

However, some months with particularly high densities in concentrated areas around Nova Scotia produced unrealistically productive (i.e., high energy) patches. These patches supported exponential growth of agents, causing them to abandon historical habitat. To achieve realistic relative population densities in the model, I performed a natural log transformation, which reduced skewness in the data, such as the extremely high prey map values that cause unrealistic population growth. This transformation alters the data by smoothing outliers and generating a more Gaussian distribution, while maintaining the character of the density distribution.

Finally, I rescaled the food maps to the same mean value used in the North Sea simulations (0.3914, unitless), which was calibrated to provide sufficient food for a stable population of around 10,000 agents in that landscape (Figure 3). I use the same mean prey value because the North Sea landscape and this study area have a nearly identical number of water cells. Additionally, due to lack of local fine-scale movement data, I assume the fine-scale movements of GoM/BoF porpoises, which are influenced by prey availability, are the same as those in the North Sea. Relative densities are maintained through the rescaling process, ensuring that individual porpoise agents will still benefit most from visiting the most productive areas in real life.

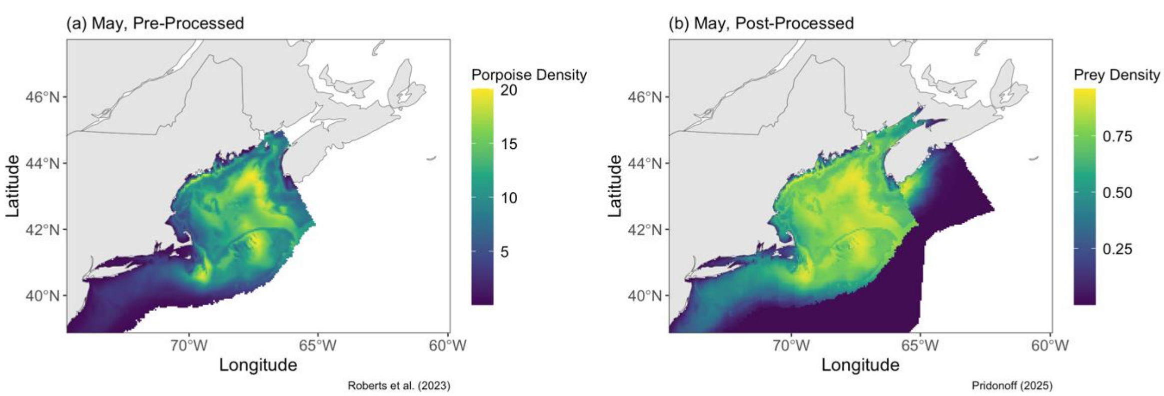

Figure 3. Example of May prey maps (a) pre- and (b) post-transformation. Transformation involved (1) temporal interpolation of areas with missing data in (December-May); (2) rescaling of newly generated data to share a maximum with the original data; (3) log-transformation of the entire map to smooth spikes; and (4) rescaling to the mean prey value of the North Sea simulations (0.3914, unitless) to properly transform the porpoise density into prey density (unitless). Base data (a) is based on survey data from 1998-2020.

Parameterization to Local Conditions

In addition to sourcing and generating maps that characterize the study area and local environmental conditions, I altered the mating day and age of maturity parameter values from the default (North Sea) values based on the findings of local GoM/BoF published literature (Table 3). Some of the parameters left unchanged may be the same or similar between the North Sea and GoM/BoF populations (Read & Hohn, 1995), while others are simply not described in local literature. For example, numerous studies document the similarities and differences between the reproduction of GoM/BoF and North Sea porpoises (Read, 1990; Read & Gaskin, 1990; Read & Hohn, 1995). In contrast, I assume the fine-scale movement behaviors of GoM/BoF porpoises are similar to those of North Sea porpoises due to a lack of studies with GPS-tracked porpoises in the study area. Table 3 displays the parameters adjusted to local values.

Table 3. Gulf of Maine/Bay of Fundy (GoM/BoF) DEPONS parameter inputs changed from the North Sea defaults. Other parameter values are either believed to be similar between the GoM/BoF and North Sea populations (Read 1990; Read & Gaskin, 1990; Read & Hohn, 1995), or data were unavailable to evaluate the differences.

Parameter	Default Value	GoM/BoF Value	Source
Tmating – mating day [day of year] (Nmean; 1 SD)	225	180	Read, 1990
Tmature – Age of maturity [years]	3.44	3.36	Read & Hohn, 1995

Scenario Descriptions

Once the model was set up, I added disturbing agents to interact with the porpoise agents. This study uses two disturbance scenarios to simulate the impacts of two types of OSW noise: ‘Construction’ and ‘Operation.’ Each scenario is compared to a third ‘Baseline’ scenario to compare effects with and without OSW impacts. Baseline simulations include only non-OSW background vessels, like fishing and cargo vessels. These were based on real data from 2023. All scenarios include the non-OSW vessels from the Baseline scenario, in addition to their named disturbance type. This accounts for the compounding effect of many, but not all, noise disturbances and increases the realism of the model landscape, given that OSW infrastructure is not the only source of anthropogenic noise in these landscapes. The Construction scenario adds example OSW construction vessels to the Baseline scenario, with no operational turbine noise. The Operation scenario only includes the noise from operating turbines and is absent of any construction noise.

Each scenario was simulated for 15 runs to account for the stochastic variation among runs, allowing the calculation of the mean and variance. Runs began with a ten-year burn-in period, during which the only impacts came from baseline vessels, followed by eight years of disturbance. During the burn-in period, the population reached a carrying capacity of approximately 10,000 porpoise agents. Scenarios assume a complete buildout of BOEM’s proposed Gulf of Maine lease areas (Table 4), though as of December 2025, only four of the eight lease areas have been leased (BOEM, 2024).

Representing Gulf of Maine wind farm impacts requires design specifications that have not yet been determined or publicized by the leaseholders. Fortunately, one can make educated assumptions based on existing resources. These include technical reports on floating OWFs (e.g., Burns et al., 2022), BOEM’s reported goals for the energy capacity of the area (BOEM, 2024), and industry consulting guides (BVG Associates, 2023), among others. The full turbine layout (Figure 2) is based on the most up-to-date reports and shapefiles of lease area extents, published in November 2024 (BOEM, 2024). Using the Create Fishnet tool in ArcGIS Pro, I distributed turbines evenly within each lease area at a 1-nm spacing (Table 4). 1-nm spacing is the most up-to-date assumed spacing, though this may change due regulatory requirements, site conditions, leaseholder preference, or due to the technical needs of floating wind infrastructure (BOEM, 2024).

Table 4. Number of Turbines by Lease Area. The number of turbines per lease area is estimated based on how many fit within each lease area using a 1-nm spacing. Asterisks (*) indicate lease areas that were leased based on bids received during the October 2024 BOEM auction.

OCS-A 0562*	OCS-A 0563	OCS-A 0564*	OCS-A 0565	OCS-A 0566	OCS-A 0567*	OCS-A 0568*	OCS-A 0569	TOTAL
119	131	116	125	116	139	145	123	1014

<u>Baseline Vessel Noise</u>

All scenarios include a baseline amount of ship activity that is separate from the projected construction vessel traffic associated with the GoM OSW developments. These baseline data are Automatic Identification System (AIS) data for 2023 made public by BOEM, NOAA, and the U.S. Coast Guard Navigation Center, and accessed via the Marine Cadastre website (NOAA Office for Coastal Management, 2024). 2023 vessel data was looped for all years of the simulations.

2023 AIS data were processed in R, including through use of the DEPONS2R package, into a format usable by DEPONS. Only ships within the study area are included, and all ship points are converted to the project's projected coordinate system (NAD 1983 Zone 19N; EPSG 26919). This process used each ship's Maritime Mobile Service Identity (MMSI; a standardized identification code), date and time, vessel type, vessel length, longitude, and latitude. Files were converted into the .json format after interpolation to 30-minute time steps and calculation of speed for each ship based on its positioning and date/time. Finally, individual ships were grouped into categories based on their type, length, and speed that share the same noise output, as defined by MacGillivray & De Jong (2021). These methods are further explained in the DEPONS v3.2 TRACE document.

Construction Vessel Noise

The Construction scenario includes ship agents traveling between Sears Island Port and each wind turbine location. This study developed an R script to generate the coordinates, ship speeds, and timestamps of each construction ship based on a hypothetical construction schedule. Similar to the AIS vessel agents used in the Baseline scenario, construction vessel agents produce noise levels modeled according to the vessel's speed, size, and type (MacGillivray & De Jong, 2021). Anchor handling tug supply (AHTS) vessels are best suited to perform most, if not all, of the FOSW installation processes, including anchor installation, towing turbines to anchors, and anchor connection (BVG Associates, 2023). The notable exceptions are the vessels used for subsea transmission cable laydown and substation installation; activities omitted from this study. This study assumes an ATHS vessel of 89.1 m length (Damen, 2025), traveling at 3.7 knots (1.9 m/s) while towing a turbine to the open ocean (BVG Associates, 2023; MacGillivray & De Jong, 2021), and 16.3 knots (8.40 m/s) when returning to port (Damen, 2025). Construction vessel agents spend four hours at a turbine to install it and eight hours at port preparing for the next tow-out. Each phase with its unique speed produces a different sound pressure level, as determined by MacGillivray and De Jong (2021).

Given the vessel speeds and presumed construction schedule, construction takes place over approximately 5 years and 11 months. This assumes one turbine is installed at a time; additional fleets of construction vessels would shorten the impact period, add additional noise to the environment, and dramatically increase costs to the developer. As noted, the final spacing may be wider than the expected 1-nm distance. Wider spacing may reduce the number of turbines that can fit within a lease area, shorten the construction period, and leave more space between turbines without audible operational noise.

Operational Noise

DEPONS can simulate noise from wind turbine operation by providing the coordinates of each turbine, SPL at 1 m, and start and end time noise production. I generate these inputs based on the above-described turbine layout (Figure 2) and the estimated SPL of 12-18 MW floating turbines proposed for the GoM. Because 12-18

MW floating turbines have yet to be built and tested for their SPL at 1 m, I rely on modeled estimates of SPL from the literature. These studies relate real-world measurements of broadband and tonal noise to parameters that may influence the SPL, such as wind speed, turbine capacity (i.e., size), and design (e.g., gear box vs. direct drive, or floating vs. fixed bottom). Stöber and Thomsen's (2021) estimates represent the highest SPL found in the literature: A 10 MW fixed-bottom turbine may produce up to 170 dB re 1 μPa broadband noise. This is louder than even Baldachini et al.'s (2024) modeled SPLs for 12-14.7 MW floating turbines, which is the only study I found with estimates for such large turbines.

I use Stöber and Thomsen's (2021) SPL to create a sound propagation curve describing the expected SPL at various distances from the sound source. Sound propagation curves are based on the inverse squares law,

$$RL = SPL - \beta log_{10}[(dist(p,k)) - \alpha(dist(m,k))]$$

where RL is the sound level received by the porpoise agent, SPL is the sound pressure level at 1 m observed by a given study (in this case, 170 dB re 1 μPa), β is the spreading loss factor (a value between 10 [cylindrical spreading] and 20 [spherical spreading]) affected principally by bathymetry, $dist(p,k)$ is the distance from the porpoise p to the sound source k, $dist(m,k)$ is the distance from the measured sound to the sound source k (1 m for Stöber and Thomsen [2021]), and α is the absorption coefficient. I set α = 0 for simplification purposes because the real value varies based on local conditions, is near 0, and only marginally would influence the shape of the curve (Ainslie & McColm, 1998). β = 15, representing a balance between cylindrical spreading – appropriate for shallow systems, where sound waves will bounce off the seafloor – and spherical spreading – appropriate for very deep systems where sound waves will attenuate before reaching the seafloor (Tsouvalas, 2020). Figure 4 shows the sound propagation curve, with a disturbance threshold T of 122.8 dB re 1 μPa corresponding to Stöber and Thomsen's (2021) modeled disturbance distance of 1.4 km for direct drive turbines.

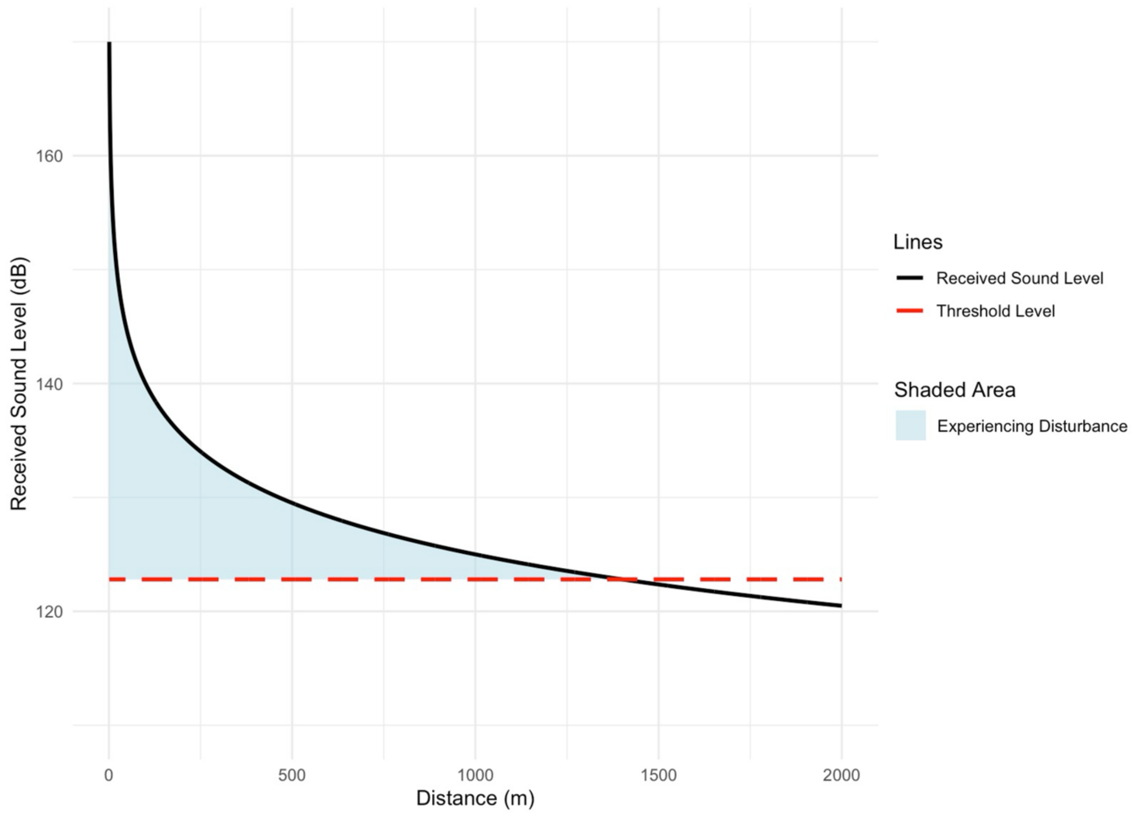

Figure 4. Sound propagation curve for operational noises. The black line shows the noise level received by a porpoise agent at a given distance. The red line shows the threshold level T (122.8 dB) a noise must exceed for a porpoise agent to experience behavioral

Analysis of Model Outputs

Unique from field and lab experiments, simulation-based experiments like this one should not use frequentist statistics like tests of significance for interpretation because one can often manufacture significant results by running an arbitrarily high number of simulations (White et al., 2014). Instead, I examine the effect size of each scenario to predict percent change of the population under various disturbances. To do so, I fit two linear mixed models (LMMs) with average yearly abundance as the dependent variable, scenario as a fixed effect, year as a continuous random effect, and simulation number as a random effect nested within scenario. The first is an additive effects model, and the second is an interactive effects model, testing the interaction between scenario and year. Similarly, I examine the deviation of a scenario's abundance from the baseline abundance at each timestep. This approach allows both a numerical and visual assessment of model results.

Movement Analysis

A key component of assessing the realism of simulations is ensuring that movements are realistic. To investigate the realism of agent movements, I compared the tracks of simulated porpoises to those of ARGOS satellite-tracked porpoises in the study area (Read & Westgate, 1997) using the DEPONS2R package (Nabe-Nielsen & Frankish, 2020). The Read & Westgate (1997) dataset includes viable tracks of 15 different porpoises, each with at least 65 days of uplinks. As such, I based movement analyses on the first 65 daily positions for each track. Viable tracks are ones that fall within the study area and do not exhibit obviously unrealistic behavior, such as cutting through large tracts of land, based on visual inspection of the tracks. Because GPS tracking (i.e., fine-scale) data are unavailable in the study area, I only analyzed and compared large-scale movements.

I compared the 15 real-world porpoise tracks to 15 simulated agent tracks run in the 'baseline' scenario setup. Each simulated porpoise was given a starting location that matched the starting location of one real-world track. This ensured that differences in local food distribution are accounted for as best as possible. Furthermore, I delayed the start of simulated agent tracking until August 15th of year 10, after the burn-in period. Waiting ten years allows agents to establish their spatial memory of food patches by the time tracking begins. I started tracking on August 15th because the real-world porpoise tracking began roughly in mid-August (range: July 29-August 26). Distributions of the GoM/BoF porpoise population and its prey vary by season (Read & Westgate, 1997; Roberts et al., 2023; Van Parijs et al., 2023), so accounting for both the proper start time and location reduces bias in the movement analysis.

I compared tracks using three metrics: home range size, maximum net squared displacement (max NSD), and track tortuosity (as measured using the sinuosity index; Benhamou, 2004). I calculated home range size (km^2) for each track using the *href* smoothing method in the R package *adehabitatHR* (Calenge 2006). Max NSD is the maximum distance between each position in the track and the start of the track, squared. Finally, tortuosity is the inverse of a path's efficiency and is represented by the sinuosity index (Benhamou, 2004). Sinuosity is a composite index of the mean cosine of changes of direction and the mean step length (Benhamou 2004). For each track metric, I compared the median values of the 15 satellite-tracked animals to the corresponding median values of the 15 simulated animals, and tested for statistically significant differences using the Mann Whitney U Test. The results of the movement analysis enabled this study to better understand the large-scale movements of local porpoises and properly interpret the validity of modeled PCoD results.

RESULTS

I successfully built a GoM/BoF formulation of the DEPONS model where the model behaved normally for the first eight years of the simulations after the ten-year burn-in period. Some components of the model, such as porpoise movements, were not fully realistic. This enabled preliminary estimates of population effects from reduced foraging success that cannot, at present, be used for management, but do demonstrate the model's ability to detect emergent population dynamics from noise stressors, including operational noise from hypothetical 10 MW turbines. Here, I present both the effects observed on the full population and in the smaller areas (blocks) around the wind farms.

Movement Analysis

In the current version of DEPONS, the large-scale movements of simulated porpoises and real, satellite-tracked GoM/BoF porpoises were significantly different across all three metrics (Mann-Whitney U Test–home range $W = 29, p < 0.001;$ maxNSD $W = 39, p < 0.01;$ sinuosity $W = 197, p < 0.001$; Figure 5). Real animals have smaller home ranges and lower max NSD than the simulated ones, but greater sinuosity in their movements, indicating real porpoises travel on more convoluted paths (Figure 5). Example tracks of real and simulated porpoises are shown in Figure 6.

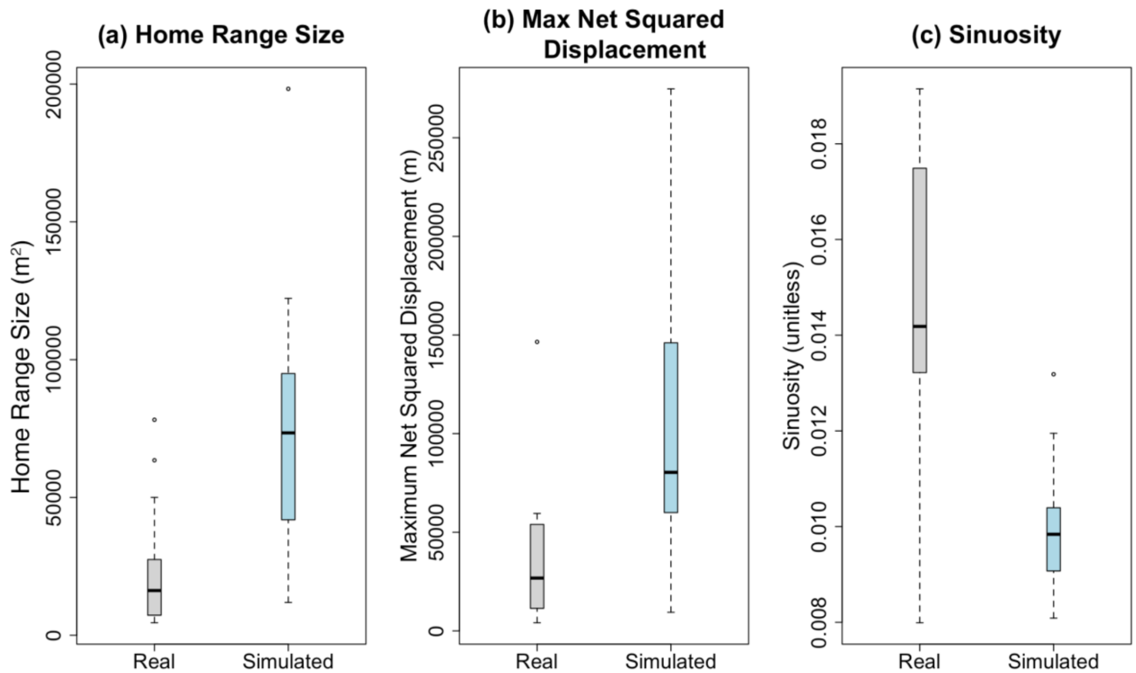

Figure 5. Boxplot showing large scale movement metric comparisons between real and simulated porpoises (agents). (a) Home range size; (b) Maximum net squared displacement (Max NSD); (c) Sinuosity. Findings are based on 65 days of continuous tracking of 15 real porpoises and 15 porpoise agents. To control for temporal and spatial variability, all simulated tracks start at roughly the same time of year as tagging (August 15) and in the same approximate location as the real porpoise to which they are being compared. Only one replicate was performed for each simulated track. m = meters; m^2 = meters squared.

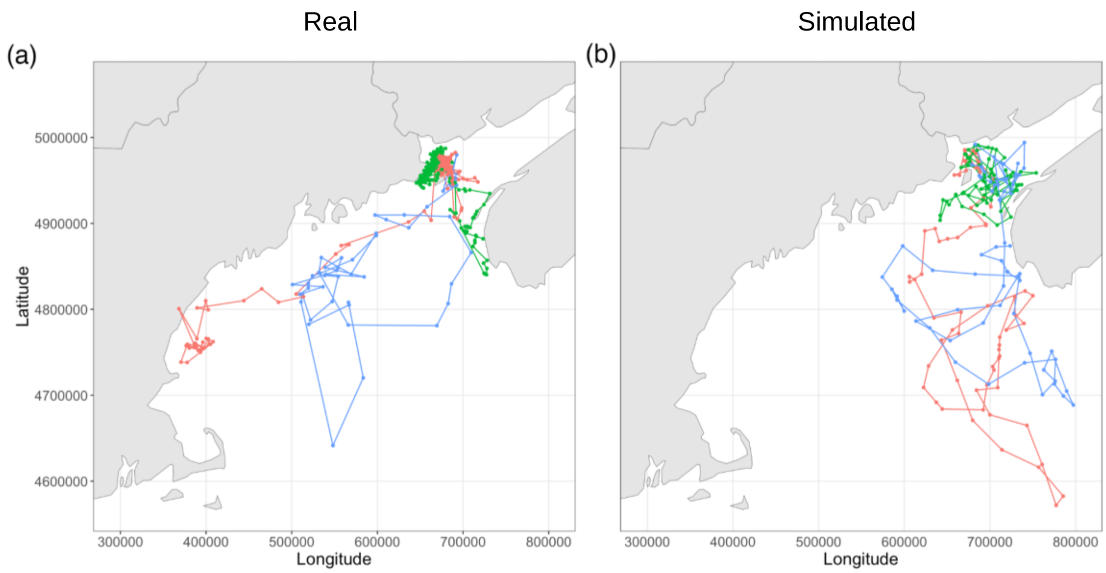

Figure 6. *Maps of three randomly selected example pairs of (a) real and (b) DEPONS simulated porpoise tracks. Tracks show 65 days of movement each. Tracks of the same color start at roughly the same location and date/time. The maps use the NAD 1983 Zone 19N projection (EPSG 26919), where latitude and longitude are measured in meters.*

Visual inspection of tracks shows they may be more similar than the summary statistics suggest. In particular, distance traveled, quantified primarily through max NSD, appears fairly consistent among individuals (same color tracks in Figure 6). However, as reflected in Figure 5, home range sizes appear to vary considerably, especially in the case of the red track. Additionally, real porpoises appear to remain in smaller areas for longer, as seen in the red and green tracks in Figure 6a, near the mouth of the Bay of Fundy.

Population Effects of Offshore Wind

DEPONS successfully simulated population abundances over 18 years (ten years of burn-in, eight years of disturbance), showing slight differences between each disturbance scenario (Figure 7). The model predicted slight declines in both the full population and wind farm blocks when porpoises were exposed to wind energy-based noises, but overall, the population remained stable around the baseline abundance in the different disturbance scenarios.

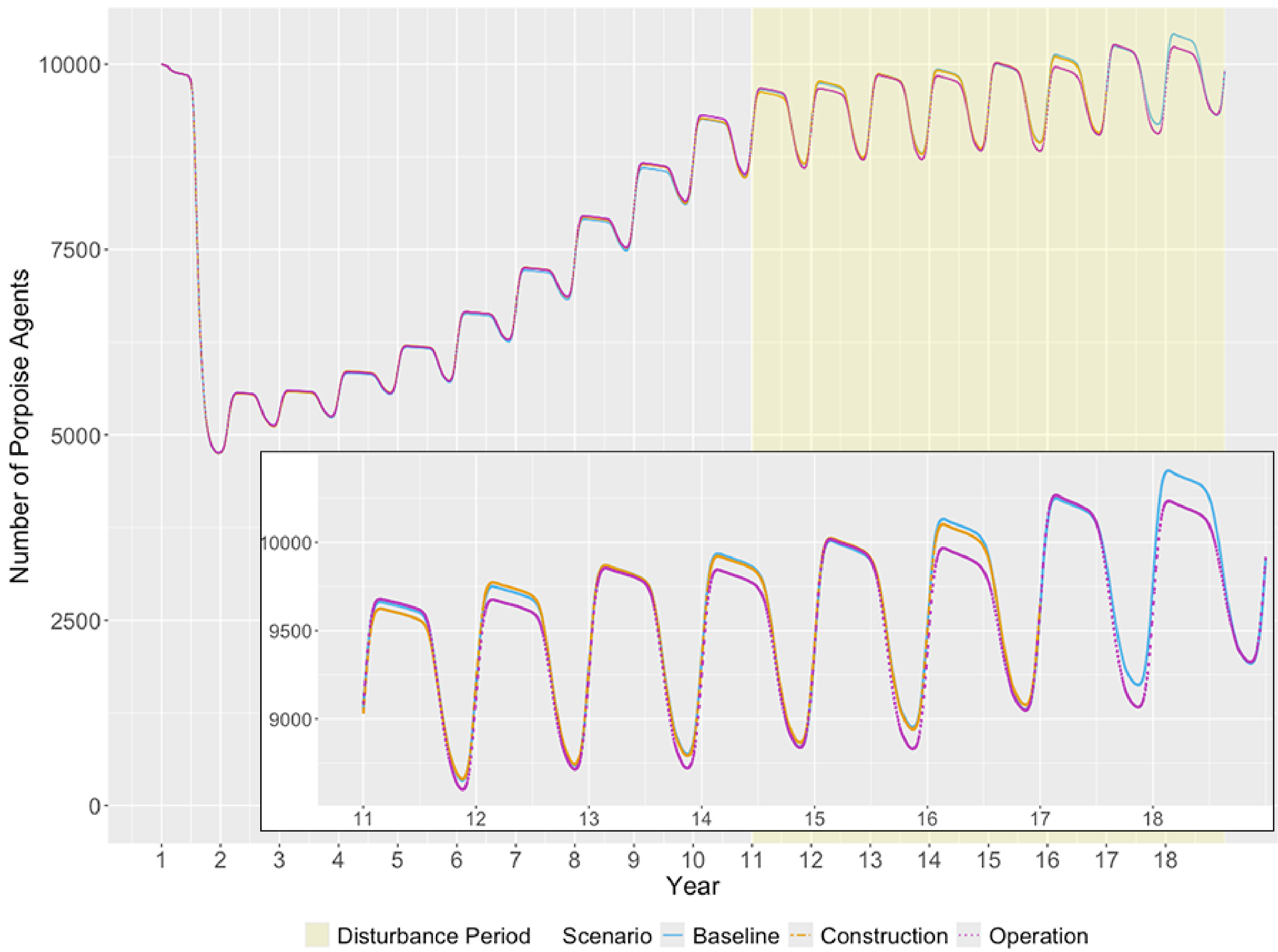

Figure 7. Population size of simulated porpoises, averaged for each scenario. Disturbances begin at the start of the 11th year of the simulation, with the Construction Scenario ending after year 16 (when construction finishes). 15 replicates were run for each scenario. The inset figure shows a zoomed-in view of the disturbance years. Light blue = baseline; orange = construction; magenta = operation.

Population-Level Effects

DEPONS detected minor population declines in the operation scenario and effectively no change in the construction scenario (Figure 8), with the simulated populations in both scenarios showing no sign of collapse throughout the disturbance period (Figure 7). Across their respective disturbance periods (six and eight years, respectively), the average deviation of the construction scenario from the baseline is -1.85 porpoise agents (*95% Confidence Interval [CI; -12.08, 8.36]*) or an approximately 0.019% decline, effectively showing no change when considering the confidence interval (Figure 8). In contrast, operation on average decreased the population by 56.23 porpoise agents (*95% CI [-78.99, -33.47]* (Figure 8) or 0.59%.

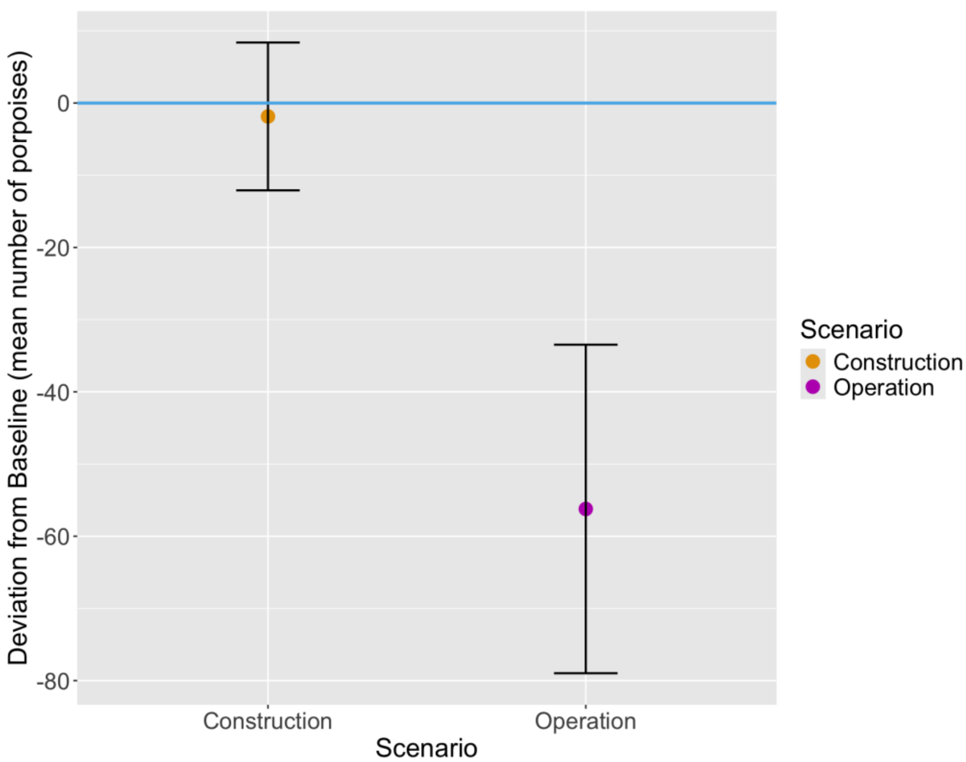

Figure 8. *Mean deviation of each scenario from the baseline (± 95% CI) averaged across disturbance years for the full GoM/BoF population. The light blue line at y = 0 represents the baseline scenario. 15 replicates were run for each scenario.*

When inspecting population effects over time, I found that construction showed a modest negative effect immediately, but that effect diminished quickly and stabilized around the baseline after year 12 (Figure 9a). By the final disturbance year, the negative effect of construction noise only yielded a 0.06% decline (6.2 porpoise agents). In contrast, the negative effect of operation started small, but increased substantially over time (Figure 9b). This is consistent with the best fitting LMM's (Model 1A; Table 5) results, which found that the negative effect of both construction and operation increased with time, but were small relative to the full population size (Table 6). In the final disturbance year, the population declined by 1.0% (98.8 porpoise agents) relative to the baseline. However, both effects are small compared to the full population size (Figure 7). These results also show that the random effect of 'run' instance is less than that of noise ("residual", Table 6), indicating that the differences between runs contributed less than unexplained variation. Results of the additive effects model (Model 2A) are also provided in Table 6.

Table 5. Model fit results of linear mixed effects models of the full population effects. Bolded text indicates that Model 1A was the best fit. 'Scenario' defines the type of impacts received in addition to baseline ship noise (construction noise or operational turbine noise). 'Run' is a covariate providing each simulation run with a unique identification code to account for random variability between simulations. Deviance and AIC are unitless.

Model	Formula	Deviance	AIC	ΔAIC	Likelihood Ratio Test
1A	**Mean Annual Abundance ~ Scenario * Year + (1 | Scenario:Run)**	**3785.7**	**3801.7**	**--**	***P = 0.02287****
2A	Mean Annual Abundance ~ Scenario + Year + (1 | Scenario:Run)	3793.2	3805.2	3.5	--

* Likelihood ratio test finds $p < 0.05$*, indicating Model 1A fits the data significantly better*

Table 6. Results of the mixed effects models, quantifying the effects on the full population. SE = standard error. Interactive effects for Model 1B are listed as not applicable (NA) because the model exclusively includes additive fixed effects.

Parameter	Intercept	Construction	Operation	Year	Construction * Year	Operation * Year	Random Effect: Run #	Random Effect: Residuals
Model 1A Effect Size (number of porpoises; ± SE)	8304.4 (± 41.39)	136.0 (± 71.4)	77.4 (± 58.5)	89.9 (± 2.70)	-10.8 (± 5.0)	-9.2 (± 3.8)	46.30	67.76
Model 1B Effect Size (number of porpoises; ± SE)	8386.7 (± 28.85)	-1.85 (± 17.39)	-56.23 (± 20.20)	84.17 (± 1.76)	NA	NA	46.12	68.66

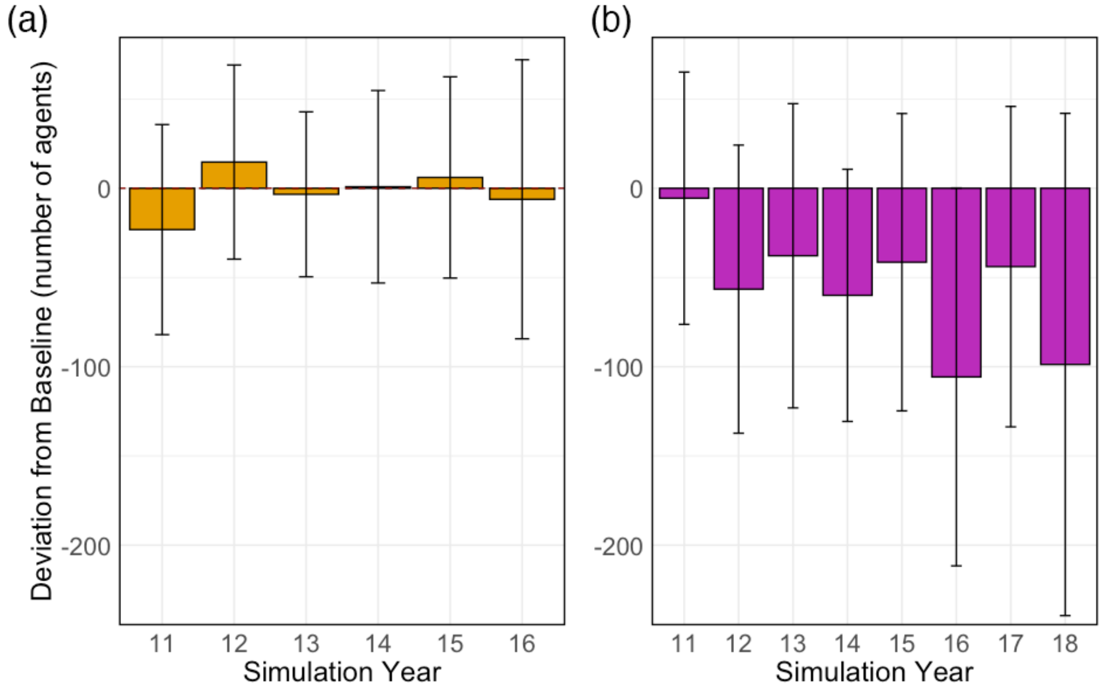

Figure 9. *Barplots of the deviation of each scenario's full population porpoise abundance from the baseline. Error bars show the standard deviation of the deviation of mean yearly abundances from baseline. (a) Construction, which takes place over six years. (b) Operation, which occurs throughout the full eight-year disturbance period. 15 replicates were run for each scenario.*

Effects Near Wind Farms

Like for the full population, DEPONS detected negative effects of construction and operational noises on porpoise abundance in wind farm block areas, though the effects were rather small. When inspecting the mean change across the full disturbance period, construction noise reduced the in-block porpoise abundance by 1.5 agents (*95% CI = 1.23)* on average, a 0.4% decline (Figure 10). Therefore, in relative terms, the noise from construction vessel activity is experienced more strongly in wind farm blocks than in the full study area. In contrast, operational noises produced more varied results with a mean drop of 0.59 agents (*95% CI = 4.73*), a 0.19% decline. Accounting for the confidence interval suggests that operation produced effectively no change

(Figure 10). However, inspecting the effects of operation over time revealed stronger effects as time progressed.

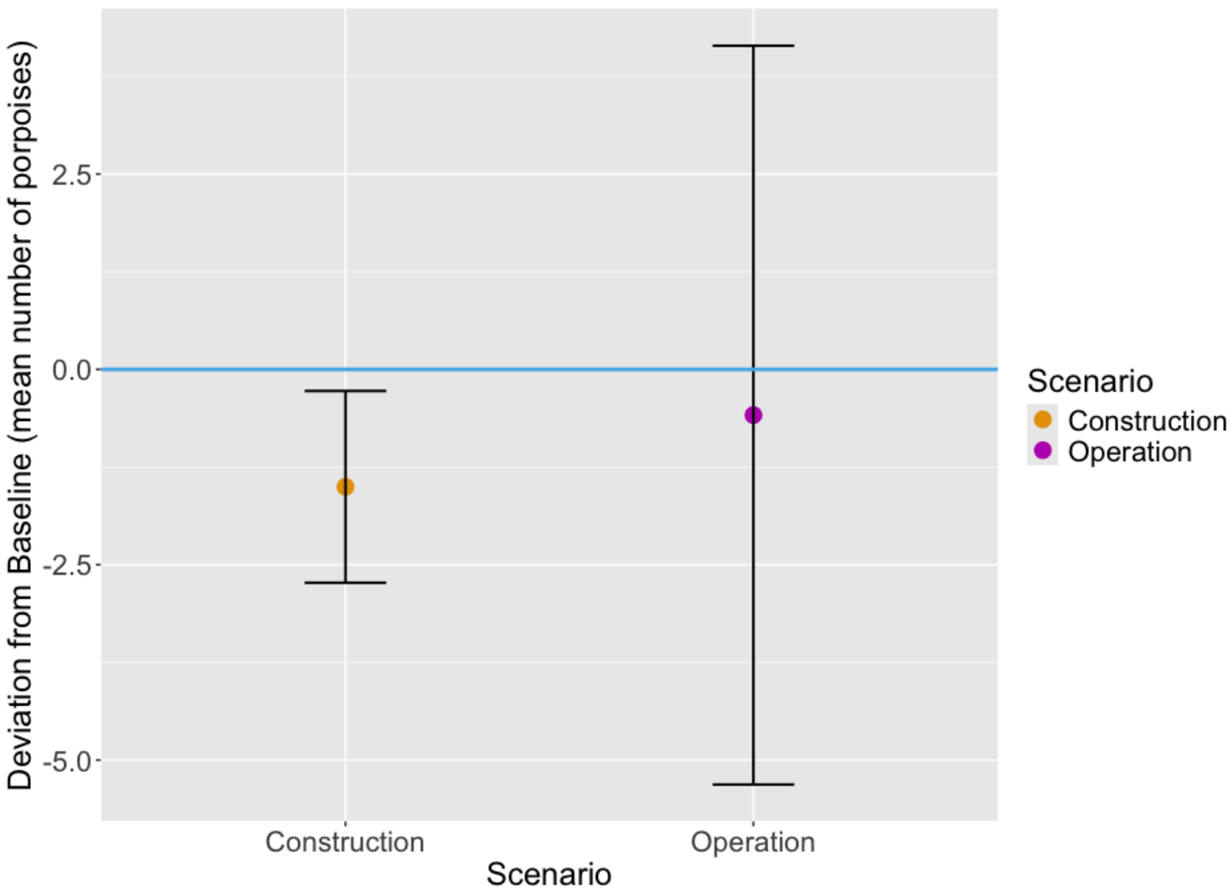

Figure 10. *Mean deviation of each scenario from the baseline (± 95% CI) averaged across disturbance years, specifically for wind farm blocks. The light blue line at y = 0 represents the baseline scenario. 15 replicates were run for each scenario.*

Construction shows no substantial effect of time in wind farm blocks, while operation had an increasingly negative effect in blocks as time progressed. Figure 11a visually shows that the minor effect of construction noise is relatively constant across the six-year disturbance period. This concurs with the results of the interactive effects LMM (Model 2B; Table 7), which found that, when considering the standard error, construction's effects did not vary substantially with time (Table 8). In contrast, Figure

11b and the same model (Table 8) indicate that operational noise has a small negative effect that increases with time, eventually exceeding the negative effect of construction vessel noise. In the final disturbance year, the abundance in wind farm blocks declined by 2.6% (8.6 porpoise agents) relative to the baseline. Because simulations were limited to 18 years total (eight years of disturbance), one cannot determine when this negative trend would stabilize. Additionally, the random effect of 'run' instance is less than that of noise ("residual"; Table 8), indicating that differences between individual runs have no meaningful effect on the model outcomes. Results of the additive effects model (Model 2B) are also shown in Table 8.

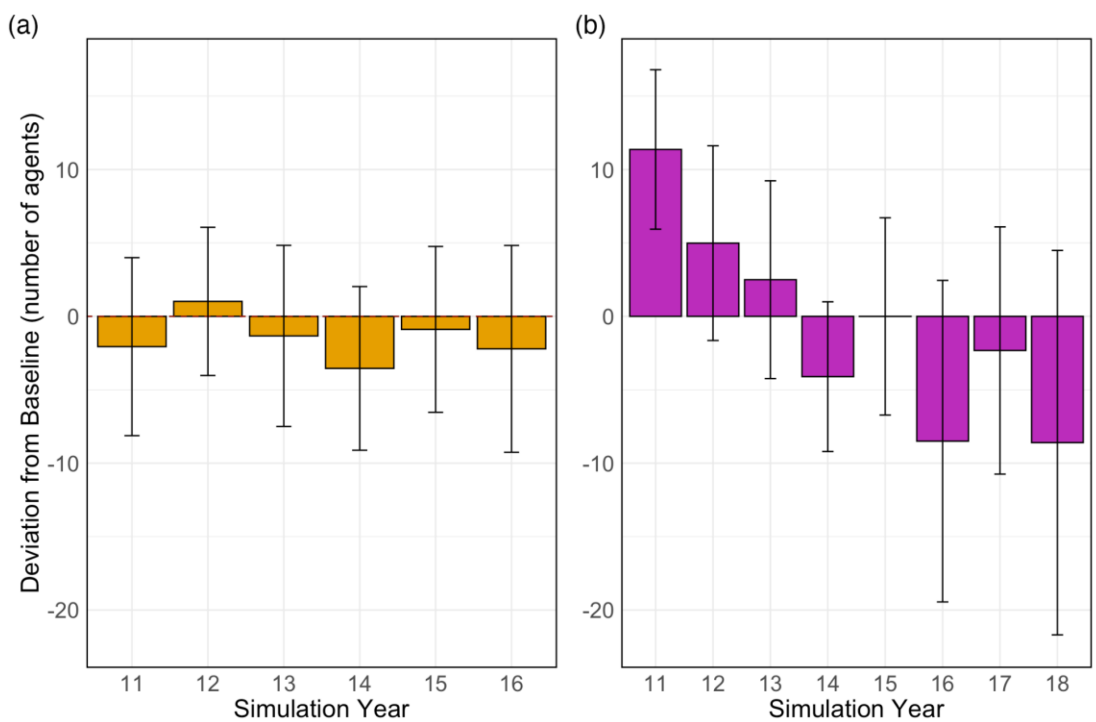

Figure 11. Barplots of the deviation of each scenario's within-block porpoise abundance from the baseline. (a) Construction, which takes place over six years. (b) Operation, which occurs throughout the full eight-year disturbance period. 15 replicates were run for each scenario. Note that construction vessels generate noise outside of wind farm blocks as well during transit.

Table 7. Model fit results of linear mixed effects models of the effects in the wind farm blocks. Bolded text indicates that Model 1B was the best fit. 'Scenario' defines the type of impacts received in addition to baseline ship noise (construction noise or operational turbine noise). 'Run' is a covariate providing each simulation run with a unique identification code to account for random variability between simulations. Deviance and AIC are unitless.

Model	Formula	Deviance	AIC	ΔAIC	Likelihood Ratio Test
1B	**Mean Annual Abundance ~ Scenario * Year + (1 | Scenario:Run)**	**2230.7**	**2246.7**	**--**	**P < 0.001***
2B	Mean Annual Abundance ~ Scenario + Year + (1 | Scenario:Run)	2274.0	2286.0	39.3	--

* Likelihood ratio test finds *$p < 0.05$, indicating Model 1B fits the data significantly better*

Table 8. Results of the mixed effects models, quantifying the effects within wind farm blocks. SE = standard error. Interactive effects for Model 2B are listed as not applicable (NA) because the model exclusively includes additive fixed effects.

Parameter	Intercept	Construction	Operation	Year	Construction * Year	Operation * Year	Random Effect: Run #	Random Effect: Residuals
Model 1B Effect Size (number of porpoises; ± SE)	397.1 (± 3.95)	4.36 (± 6.84)	34.8 (± 5.6)	-5.92 (± 0.26)	-0.44 (± 0.48)	-2.44 (± 0.40)	3.624	6.560
Model 2B Effect Size (number of porpoises; ± SE)	412.9 (± 2.85)	-2.72 (± 1.62)	-0.58 (± 1.56)	-7.01 (± 0.18)	NA	NA	3.484	7.079

DISCUSSION

This study sought to test the agent-based model DEPONS in a new environment to test its accuracy and develop preliminary estimates of harbor porpoise population effects of local offshore wind energy noises. I found DEPONS can be used in new environments, such as the Gulf of Maine and Bay of Fundy, but further calibration based on local movement data is needed to produce sufficiently realistic movements. This study demonstrated that population effects could be detected, implying that once movements are re-parameterized, current parameters are recalibrated, and a stable population can be simulated for a full study period (i.e., more than eight years), DEPONS can be used to inform management decisions off the U.S. and Canadian east coasts. Importantly, while DEPONS is typically used to simulate construction and vessel-based noise, this study is one of the first examples of DEPONS successfully simulating operational broadband noises and predicting their effects, demonstrating the expanding capabilities of the tool. Through re-parameterization and recalibration, ideally bolstered by additional GPS tracking data on GoM/BoF porpoises, agent-based models like DEPONS will be well positioned to predict cumulative, population-level effects of OSW noises on harbor porpoises.

Findings and Future Directions

Porpoise Movements

Pertaining to the first goal of this study, I found that porpoise agent movements are not yet representative of the GoM/BoF population's movements (Figure 5), and will need to be re-parameterized before use in management. Analysis of real (Read & Westgate, 1997) and DEPONS simulated porpoise movements found that simulated porpoises had larger home ranges, longer maximum net squared displacement distances, and less sinuosity. These differences were significant, though there were overlaps in the real and simulated data in all three metrics (Figure 5). Such differences are likely to influence their survival and population dynamics. The movement tracks and statistics suggest that simulated porpoises give up on using local resources too fast, causing them to use large-scale movements too often. Through this, simulated porpoises presumably have access to more foraging grounds and may be more resilient to local disturbances because they can presumably find food elsewhere. However, regularly moving longer distances does require additional energy. Lower sinuosity may also suggest that simulated porpoises recall the locations of food patches too well and move more directly to them, spending less time searching randomly for prey. These agent behaviors can be fixed by calibrating the parameter ttodisp (time to onset of dispersal).

These differences in movements, though statistically significant, may not be particularly meaningful biologically. Visual inspection of tracks indicates that porpoises are capable of moving similar distances in real life and in the simulation (Figure 6). Even among individuals (Figure 6, tracks of the same color) porpoises appear to be capable of moving long distances across the landscape, emphasizing their ability to search new areas for prey resources.

While re-parameterization may be vital to improving the realism of the model, the satellite tracking data also contains its own spatial bias that may suggest the ‘real’ movements measured are not representative of the full population. All harbor porpoises in the Read and Westgate (1997) dataset were tagged in the Bay of Fundy. Those porpoises appear to have naturally smaller home ranges than the full population given that those tagged (Figure 12) did not venture as far south and offshore, or southeast of Nova Scotia as suggested by the Roberts et al. (2023) density distribution maps. While this cannot be verified through this study, it is possible the movements of the full population are more similar to the movements of the simulated animals. To answer this question, one would need tracking data from porpoises originating from other habitats within the GoM/BoF population’s range. Furthermore, future studies could benefit from tracking porpoises for longer timeframes to see how seasonal activity, like the population’s north-south movements, affect movement metrics.

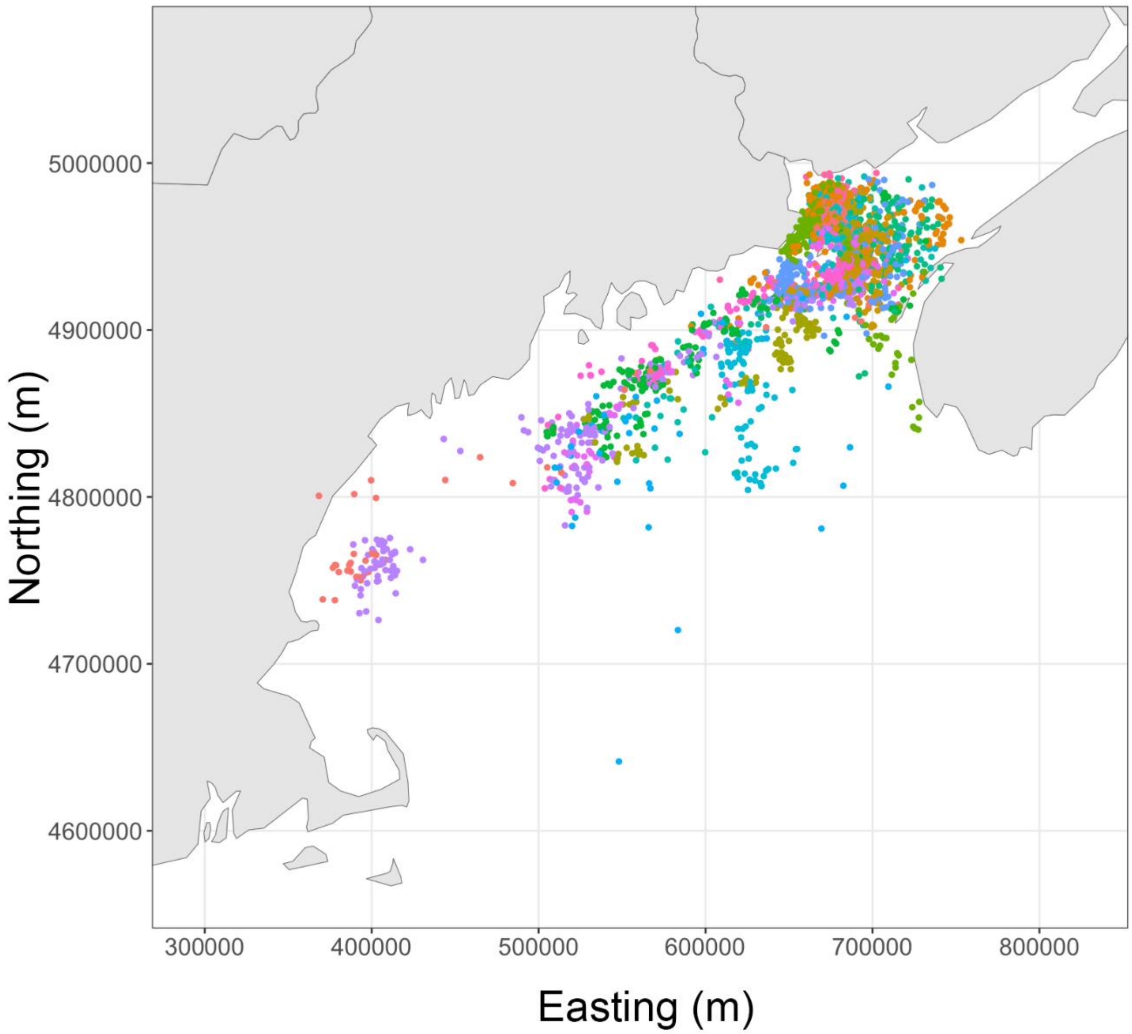

Figure 12. Map of locations received from satellite tracked porpoises in the Gulf of Maine and Bay of Fundy (tracking data provided by Read & Westgate, 1997). The map uses the NAD 1983 Zone 19N projection (EPSG 26919).

Another potential contributor to the significant differences in real and simulated movements pertains to the prey map transformations I performed (Figure 3). I log-transformed the prey maps to generate a stable carrying capacity for the disturbance period (years 11-18) because the untransformed prey maps produced unrealistic spikes in the population. Untransformed maps contain extremely high energy food patches very close to each other, making it easy for porpoise agents to acquire abundant energy without expending much. Further, close proximity of patches allowed agents to easily recall their locations and pass that information along to their calves. Log-transformation smoothed these extremes, but also reduced the relative importance of the most profitable northern areas, like the Bay of Fundy. This unsurprisingly may have compelled simulated porpoises to use wider ranging habitats and travel farther south than real porpoises.

Re-parameterizing the movements to achieve realism is necessary to trust that the findings of the model reflect the likely behaviors of local porpoises. Future re-parameterization must identify any problematic parameters leading to unrealistic movements and test alternative values using standardized parameter sensitivity analysis methods (Stillman et al., 2015). I suspect movements can be made more realistic by reducing dispersal distances and incorporating decay into the spatial memory of porpoises. Presently, LSM persistent spatial memory does not deteriorate, allowing agents to revisit distant sites when their energy runs low with high fidelity. Effectively, the strong memory allows porpoises to avoid competition for prey and make potentially unrealistically informed decisions on the cost-benefit of traveling to distant foraging grounds. While this has not caused unrealistic movements and population growth in simulations of European habitats, this may have contributed the significantly larger home range sizes and max NSD I observed, as well as unrealistically large population sizes after year 18. Through year 18, the GoM/BoF population dynamics were realistic enough to make preliminary PCoD inferences. However, after year 18, I would often observe the population abundance begin to spike and grow seemingly without constraint through the initial 50-year simulations. Finding the proper values for these parameters may solve both issues.

Normally, this kind of study might also use local GPS tracking data to properly parameterize the fine-scale movements of agents. Unfortunately, these data have not been collected for the GoM/BoF population, so I assumed the fine-scale movements of European and GoM/BoF porpoises were similar. Future efforts should include GPS tracking of GoM/BoF porpoises, as the fine-scale movements of the population have not been documented. By providing this type of data for comparison, U.S. and Canadian models can become realistic enough to inform design and management, like siting, turbine spacing, construction schedule, and technology (e.g. direct drive vs. gear box system).

Population Consequences of Noise Disturbance

As discussed, this study's findings are preliminary and cannot be used to inform management, though they may provide initial insights into the population consequences of OSW noises on GoM/BoF harbor porpoises. Recognizing the limitations of the model results, I found that, first, OSW noises contributed to reductions in porpoise survival and population size, but that these losses were relatively small and did not hinder population viability (Figure 7). Second, construction produced the strongest small-scale (within wind farm blocks) effects, but operation produced the strongest effects on the whole population.

These results suggest that operational noises from larger, louder turbines, have the potential to contribute to porpoise mortality and lower reproductive success through displacement. If turbines are sufficiently loud, porpoises can be deterred from otherwise profitable foraging grounds, and if they do not find other nearby food patches, they will fail to meet their energetic needs. Porpoises in poor health have fewer calves and become increasingly prone to mortality (Gallagher et al., 2021b). The larger overall effect of operation suggests that quieter, but more widespread disturbances may foster relatively more deterrence. However, at present, model results do not show a dangerous level of mortality that threatens population viability. In fact, noise from both construction and operation still allowed the vast majority of porpoises to use the wind farm blocks. This suggests that the disturbances do not create true habitat loss, but do marginally reduce local activity and overall population health. Looking at this a different way, if one assumes porpoises cannot forage at in the areas where they can hear turbines, they lose access to foraging opportunities in approximately 6,200 km^2, or 1.5% of the GoM/BoF landscape. This may suggest that, because operational effects on the full population were smaller (on average 0.59%), operation does not cause full exclusion from the areas where noises can be heard.

When comparing the effects of operation and construction to each other, their strength varied based on the spatial scale at which they were examined. Operational noise effects were stronger than construction effects at the full population scale (Figure 8; mean 0.59% vs 0.019%), but on average lower than, if very similar to, construction effects at the wind farm block scale (Figure 10; mean 0.19% vs 0.4%). It is unclear if there is much biological significance to the differences observed at the wind farm scale. It could imply that construction noise causes distributional shifts, and that displaced porpoises found sufficient food elsewhere to minimize mortality. Longer-term studies would help ascertain if these shifts would be temporary and if so, how quickly normal activity would resume.

While on average, operation had a smaller effect in wind farm blocks, it did produce an increasingly negative effect over time at both spatial scales (Figures 9 and 11, Tables 6 and 8). This suggests that the population consequences from sustained noises could be greater than what I observed during this study's short disturbance period. Specifically, this effect could lead to a more substantial reduction in the population's carrying capacity than what was measured, though this reduction is likely modest based on my preliminary results. It is important to note that the observed negative effect over time, as illustrated by the interactive effects model's results, is only accurate in the short time frame of this study (6-8 years). Over a longer disturbance period, I expect the population to stabilize at a new carrying capacity and not continue to decline indefinitely. Future studies will benefit from a longer disturbance period (e.g., 30 years) to fully assess the trend and magnitude of operational noise effects.

This study's findings suggest that the quieter, continuous, and more widespread operational noises of larger turbines can lead to stronger effects than the louder, higher frequency, relatively brief, and geographically-constrained construction vessel noises. This stands in contrast to historical studies on the impacts of pile driving and operational noises from smaller turbines, which typically found that impulsive construction noises were the greater threat (e.g., Bellman et al., 2023; Tougaard et al, 2020). This may still be the case for wind farms in shallow water habitats where pile driving is feasible. Another caveat is that the operational noises must be loud enough to cause behavioral responses (e.g., fleeing, avoidance, or limiting vocalizations), at least over 120 dB re 1 μPa (Center for Marine Acoustics, 2023). (Note: The low-frequency noises of operation typically cannot mask the high-frequency communications of harbor porpoises [Tougaard et al., 2009]). Negative behavioral responses have rarely been observed at operating wind farms to date, but most studies have been on turbines less than a quarter of the size of proposed turbines (Risch et al., 2023; Scheidat et al., 2011; Tougaard et al., 2020). Real world measurements of larger (12-18 MW), likely louder (Tougaard et al., 2020) floating turbines are needed to confirm if modeled noise levels used (Stöber & Thomsen, 2021) are reliable or need to be adjusted. Additionally, use of higher resolution sediment grain size maps may improve accuracy, as grain size influences how sound is reflected off the seafloor. Sediment grain size matters more when the habitat is shallow and sounds are loud, which is not the case here given the GoM is fairly deep (120-200 m in the wind farm areas), and pile driving is not expected. In summary, to estimate a given wind farm's population consequences requires local knowledge on habitat, construction methods, and turbine model, at the very least. Sensitivity analyses can also be useful in determining which inputs or parameters contribute most to changes in model outcomes, allowing managers prioritize their data collection efforts.

Due to challenges with model reliability after year 18, I was not able to use DEPONS to examine recovery of the simulated population after construction cessation. However, studies like Teilmann and Carstensen (2012) found that populations recovered in the North Sea after more severe, pile driving-based construction activities, with recovery times varying from days to years. Because both the North Sea and GoM/BoF are heavily trafficked areas, I assume observed effects would be temporary and the GoM/BoF population would recover. In contrast, the effects observed by operational noise may constitute a longer-term reduction in carrying capacity borne out by avoidance of noisy areas. Nabe-Nielsen et al. (2018) also offers insights on the lowest-impact construction schedule, based on DEPONS simulations, that may further mitigate harm to harbor porpoise populations. Principally, constant and drawn-out construction in high-quality foraging areas leads to the most severe declines. Populations were less affected by a ‘random’ ordering of turbine construction. Additionally, population effects were smaller when there were breaks between pilings. Because floating arrays require each turbine to be towed to the site, they naturally already have breaks close to the ‘slow’ scenario in Nabe-Nielsen et al. (2018): 44 hours between each turbine visit in this study’s simulations, compared to 24 hour breaks in the ‘fast’ scenario and 48 hour breaks in the ‘slow’ scenario.

Wind Farm Accuracy

The population consequences found may change if the GoM wind developments are different than what was modeled. Because no floating wind farms have been deployed in these waters, I was forced to make informed assumptions about aspects like construction schedule and turbine spacing. While all assumptions were based on, to my knowledge, the best available peer-reviewed literature, technical reports, and industry specifications, discrepancies with the final design are likely. This study’s setup was sufficient to test the effectiveness of the model in part by producing reasonably accurate OSW impacts. Nevertheless, improvements can be made. One such improvement pertains to the baseline vessel activity.

Ships from the 2023 AIS dataset occasionally move through the proposed wind farm areas. This may have led to stronger modeled effects inside wind farm blocks due to an agent being disturbed by multiple sources that will not be present simultaneously in real life. In contrast, non-OSW ships are expected to reroute around lease areas (BOEM, 2024). This may have a juxtaposing effect of increasing the density of traffic outside wind farms and allowing wind farms to act as refuges from vessel noise, given that operational noise is relatively low compared to high ship traffic (Bellman et al., 2023; Stöber and Thomsen, 2021; Tougaard et al., 2020). There will of course be OSW maintenance vessels accessing each turbine approximately once or twice a year for scheduled maintenance (Business Norway, 2021), so these ships in the wind farm blocks may not be a notable problem until maintenance vessels are simulated.

A key discrepancy is the number of lease areas developed, and therefore the spatial extent of the noise disturbances. Over the course of this study, the four unleased areas were withdrawn from OSW development (The White House, 2025), meaning that only four of the eight have a potential pathway for development in the near future. Regardless, I chose to model the full buildout to make predictions about the most impactful scenario, which includes if all lease areas are eventually developed. Evidently, this renders the observed population effects especially conservative. Observed declines may be overestimates of what would actually occur. Future modeling efforts with a refined DEPONS model can simply perform the same runs with only the leased areas.

Finally, several ecological processes are absent from DEPONS, including the habituation of porpoises to continuous noise and the artificial reef effect. I estimated that operational noises from large turbines may contribute to porpoise mortality through deterrence from/avoidance of suitable foraging habitat (Figures 8 and 9; Table 6). Porpoises that live in loud environments (be it from anthropogenic or natural sources) are often less disturbed by the addition of wind farm operational noises (Nabe-Nielsen et al., 2014). Furthermore, porpoises grow accustomed to and behave normally in the presence of low-level continuous noises, including post-construction (Brandt et al., 2011; Tougaard et al., 2006; Teilmann & Carstensen, 2012). Both of these phenomena may apply to the Gulf of Maine study area, where shipping traffic is abundant and porpoises have ample habitat to avoid operational noises and return when more habituated to the new noise. Additionally, while I model a constant SPL of 170 dB, this will vary based on wind speeds. High wind speeds naturally produce louder environmental noises, meaning operational noises may not always be detectable above ambient conditions (Tougaard et al., 2020). Finally, turbines often function as artificial reefs, attracting sessile invertebrates, creating more biodiverse habitats, and eventually attracting potential porpoise prey (Gill et al., 2020; Stöber & Thomsen, 2021). This effect may draw porpoises to more profitable prey aggregations near turbines and offset the stress or deterring effect of operational noise.

Ultimately, this study and others (Koschinski et al., 2003; Risch et al., 2023) have demonstrated that operational noises can impose quantifiable population consequences to porpoises and should be mitigated. To minimize these impacts, I suggest installing turbines that use a direct drive mechanism instead of a gear box, reducing operational noise by approximately 10 dB re 1 μPa, which translates to an approximate 1.4 km disturbance distance for a 10 MW turbine, instead of 6.3 km (Stöber & Thomsen, 2021). I also found that siting turbines in less utilized habitats (i.e., farther offshore and in deeper waters), led to minimal losses that might be more drastic if installed close to the Maine or Nova Scotian shores. The offshore wind industry and scientific community will benefit from measurements of the operational noise levels of large (10-18 MW) turbines to appropriately site wind farms and determine turbine spacing. Finally, the best way to minimize porpoise losses may actually be to mitigate other types of impacts, especially fisheries bycatch, noise from oil and gas seismic surveys, and climate change-driven changes in prey distribution and size. These represent the potentially greater causes of health and population declines than offshore wind noises (Gallagher et al., 2021a; Gallagher et al., 2021b; NMFS, 2022). By reducing reliance on fossil fuels and working with fishermen to minimize bycatch, any marine mammal effects from offshore wind noise may be compensated for multiple times over.

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