Assessing the exposure of three diving bird species to offshore wind areas on the U.S. Atlantic Outer Continental Shelf using satellite telemetry

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Abstract

Aim: The United States Atlantic Outer Continental Shelf (OCS) has considerable offshore wind energy potential. Capturing that resource is part of a broader effort to reduce CO₂ emissions. While few turbines have been constructed in U.S. waters, over a dozen currently planned offshore wind projects have the potential to displace marine birds, potentially leading to effective habitat loss. We focused on three diving birds identified in Europe to be vulnerable to displacement. Our research aimed to determine their potential exposure to areas designated or proposed for offshore wind development along the Atlantic OCS.

Methods: Satellite tracking technology was used to determine the spatial and temporal use and movement patterns of Surf Scoters (Melanitta perspicillata), Red-throated Loons (Gavia stellata) and Northern Gannets (Morus bassanus), and calculate their exposure to each offshore wind area. We tagged 236 adults in 2012–2015 on the Atlantic OCS from New Jersey to North Carolina; an additional 147 birds tagged in previous tracking studies were integrated into our analyses. Tracking data were analysed in two-week intervals using dynamic Brownian bridge movement models to develop composite spatial utilization distributions. For each species, these distributions were then used to calculate the spatio-temporal exposure to each offshore wind area.

Results: Surf Scoters and Red-throated Loons were exposed to offshore wind areas almost exclusively during migration because these species were distributed among coastal and inshore waters during winter months. In contrast, Northern Gannets ranged over a much larger area, reaching farther offshore and south in winter, thus exhibited the greatest exposure to extant offshore wind areas.

Conclusions: Results of this study provide better understanding of how diving birds use current and potential future offshore wind areas on the Atlantic OCS, and can inform permitting, risk assessment and pre- and post-construction impact assessments of offshore energy infrastructure.
1 | INTRODUCTION

Wind power is increasingly recognized as an accessible, renewable energy source which can help meet growing energy requirements while mitigating the environmental impacts of fossil fuel-based energy generation (Allison et al., 2008; Bailey et al., 2014; Bruckner et al., 2014; Snyder & Kaiser, 2009). In Europe, offshore wind production has grown rapidly, with over 22 GW of generation capacity produced as of the end of 2019 (WindEurope, 2020). While few offshore wind turbines have been constructed in the United States to date, there is extensive wind energy potential in U.S. waters and a number of major development projects are currently in the planning phases (BOEM, 2019). This is particularly true of the Atlantic Outer Continental Shelf (OCS; BOEM, 2017), where the first U.S. offshore wind facility became operational in state waters of Rhode Island in late 2016 (Ørsted, 2019).

The shallow waters of the Atlantic OCS constitute a complex, highly productive ecosystem that exhibits variable temporal and geographical conditions. The area’s high productivity is driven by the influence of the Gulf Stream to the east, and a series of large estuaries to the west (Aquarone & Adams, 2018). This region is also a focus for offshore wind development because it exhibits some of the highest offshore wind resource potential in U.S. waters (Musial et al., 2016), and is close to densely populated metropolitan areas with high energy demands. The rapid development of offshore wind facilities in Europe and substantial movement towards widespread development in the United States has led to concerns over potential adverse effects on wildlife that use the marine environment (Drewitt & Langston, 2006; Goodale & Milman, 2016; Schuster et al., 2015; Snyder & Kaiser, 2009). For birds, these effects include disturbance during site development, mortality from collision with turbines and displacement leading to effective habitat loss (Allison et al., 2008; Best & Halpin, 2019; Dierschke et al., 2016; Drewitt & Langston, 2006; Fox et al., 2006; Hüppop et al., 2006).

Loons, gannets and scoter species are highly sensitive to displacement from wind energy developments (Best & Halpin, 2019; Fox et al., 2006; Wade et al., 2016). Displacement could lead to reduced foraging opportunities, impact individual fitness and ultimately affect population trends (Drewitt & Langston, 2006), but may reduce their risk of collision with turbines. These species also exhibit different foraging strategies, exploit different marine habitats during the migration and wintering periods of their annual cycles (Nisbet et al., 2013) and are considered to be of management and/or conservation concern in the United States (MANEM, 2006; USFWS, 2008). As these species are predicted to be exposed to offshore wind development along the Atlantic OCS (Goodale et al., 2019), offshore wind poses a novel and emerging risk.

Surf Scoters (Melanitta perspicillata) are northern boreal forest breeding sea ducks and closely related to Common Scoters (M. nigra; heavily studied in Europe). The eastern North American population migrates to the Atlantic OCS and uses the area heavily in winter (SDJV, 2015). They forage on bivalves and other benthic invertebrates and generally winter in shallow inshore waters or out over large offshore shoals (Anderson et al., 2020). Avoidance of offshore wind turbines can lead to permanent or semi-permanent displacement for some sea ducks (Desholm & Kahlert, 2005; Larsen & Guillemette, 2007); however, the degree of displacement may lessen several years after construction, due to changes in behaviour, food resources or other factors (Leonhard et al., 2013; Petersen & Fox, 2007). Tracking studies suggest scoters return to the same wintering areas each season (SDJV, 2015), emphasizing their susceptibility to displacement from important resources.

Red-throated Loons (Gavia stellata) that breed across a broad swath of the Nearctic use the Atlantic OCS during winter and migration (Warden, 2010). They are Arctic or subarctic breeders and opportunistic foragers, mainly mid-water or benthic fishes in both freshwater and coastal marine environments (Rizzolo et al., 2020). In Europe, they have been documented to strongly avoid offshore wind developments (Dierschke et al., 2016), initiating an avoidance response as far as 16 km from an operational facility (Heinänen et al., 2020; Mendel et al., 2019), and may also be displaced by boat traffic associated with construction and maintenance activities (Mendel et al., 2019).

In North America, Northern Gannets (Morus bassanus) breed in six colonies in Atlantic Canada and use the Atlantic OCS during winter and migration, wintering as far south as the Gulf of Mexico (Montevecchi et al., 2012). They are opportunistic foragers, focused on surface-schooling pelagic forage fish (Mowbray, 2020). Capable of long-distance oceanic movements, they generally migrate on a broad front across the Atlantic OCS (Fifield et al., 2014), which may increase their exposure to offshore wind facilities (Stenhouse et al., 2017). Satellite tracking studies and surveys in Europe indicate that they strongly avoid offshore wind developments (Cook et al., 2012; Dierschke et al., 2016; Garthe et al., 2017; Hartman et al., 2012; Krijgsveld et al., 2011; Skov, 2018; Vanerman et al., 2015).

Marine birds employ varied, sometimes specialized and sometimes flexible foraging and migratory behaviours to exploit different dynamic ocean habitats (Schreiber & Burger, 2001). As a result, these species interactions with, and exposure to, offshore wind facilities have spatial and temporal components that need to be considered (Best & Halpin, 2019). Fixed-area surveys (aerial and boat-based) alone may not always detect these components at needed scales (Phillips et al., 2019). Exposure may be dependent on the intensity and timing of habitat use within the vicinity of wind energy...
development areas during the non-breeding season and migration. Tracking studies are capable of addressing these questions and play key roles in understanding marine bird exposure to offshore wind facilities, and informing permitting and management decisions (Allen & Singh, 2016; Goodale & Milman, 2020; Montevecchi et al., 2012).

We used satellite tracking data to assess the exposure of Surf Scoters, Red-throated Loons and Northern Gannets to existing and potential offshore wind areas in Federal waters of the Atlantic OCS, defined as Lease Areas (areas currently leased by developers), Wind Energy Areas (areas designated for development, but not leased) and Call Areas (potential development areas being evaluated by the federal government; BOEM, 2019; see Appendix S1). Specifically, we focused our analysis on three questions: (1) Do the study species have differential exposure to these offshore wind areas? (2) Which study species are exposed the most and, thus, may be at greatest risk? And (3) does exposure to these offshore wind areas change during different periods of the non-breeding season? We interpret our findings in the context of permitting and monitoring of offshore wind areas on the Atlantic OCS.

2 METHODS

2.1 Field efforts

In January–March of 2012–2015, the three focal species were captured within their wintering ranges in areas of known high relative density (Winship et al., 2018) on the Atlantic OCS–the Chesapeake Bay (Maryland and Virginia), Delaware Bay (Delaware and New Jersey) and Pamlico Sound (North Carolina; Table 1). Northern Gannets and Red-throated Loons were captured from small boats using night-lighting (Whitworth et al., 1997). Surf Scoters were either captured using the same night-lighting technique or with over-water mist nets during daylight hours (see Spiegel et al. [2017] for further details on capture methods). Captured birds were weighed and banded with a standard U.S. Geological Survey (USGS) metal band. Upon capture, individuals in apparent good condition and of suitable body weights were transported to a veterinarian experienced in avian surgery who implanted intra-abdominal platform terminal transmitters (PTTs) with external antenna (see Ford et al., 2017) based on standard surgical techniques (Korschgen et al., 1996; Mulcahy & Esler, 1999). Following implantation, when birds were cleared for release by the veterinarian, they were returned to the area of capture and released.

Additional data on Surf Scoters and Northern Gannets tagged with PTTs as part of prior field efforts from the following studies were also included in the analysis. In 2001–2005 and 2011–2013, Surf Scoters were captured using various techniques, including over-water mist nets, net-gunning from a boat, night-lighting or drive trapping moulting birds into submerged gill nets, and tags were implanted as described above (SDJV, 2010). In September of 2008–2010, Northern Gannets were captured with a noose pole at two breeding colonies (Cape St. Mary’s and Funk Island) in Newfoundland, Canada or by dip netting from a small boat in the waters adjacent to these sites, and PTTs were taped to the underside of the central rectrices (Montevecchi et al., 2011).

We attempted to reduce movement bias resulting from capture and marking by excluding the first 14 days of tracking data (Lamb et al., 2020; Mulcahy & Esler, 1999). Given the efficiency of the attachment process, birds with tail-taped tags were considered less compromised than surgically implanted birds, so we waived the threshold requirement for these birds.

2.2 Data management and analysis

The PTTs we deployed from 2012 to 2015 were designed to provide the greatest resolution of movement data during the winter months, while prolonging their longevity as much as possible (see Spiegel et al., 2017). PTTs from prior studies included in our analyses

| Species           | Year       | Location deployed | State or Province          | n (tail/implant) |
|-------------------|------------|-------------------|----------------------------|------------------|
| Surf Scoter       | 2013–2015  | Delaware Bay      | New Jersey/Delaware        | 0/18             |
|                   | 2012, 2013, 2015 | Chesapeake Bay     | Maryland/Delaware          | 0/38             |
|                   | 2012, 2014, 2015 | Pamlico Sound      | North Carolina             | 0/19             |
| Red-throated Loon | 2012–2014  | Delaware Bay      | New Jersey/Delaware        | 0/24             |
|                   | 2012       | Indian River Bay  | Delaware                   | 0/3              |
|                   | 2012–2015  | Chesapeake Bay    | Maryland/Delaware          | 0/24             |
|                   | 2012–2015  | Pamlico Sound     | North Carolina             | 0/35             |
| Northern Gannet   | 2012       | Cape St. Mary’s   | Newfoundland & Labrador    | 9/0              |
|                   | 2012–2014  | Delaware Bay      | New Jersey/Delaware        | 0/6              |
|                   | 2014       | Indian River Bay  | Delaware                   | 0/1              |
|                   | 2012–2015  | Chesapeake Bay    | Maryland/Delaware          | 3/45             |
|                   | 2013–2014  | Pamlico Sound     | North Carolina             | 0/11             |
were programmed with varying duty cycles, depending on study objectives (SDJV, 2015). Telemetry data from PTTs were collected using the Argos satellite system (Argos, 2019) and filtered using the Douglas Argos Filter (DAF; Douglas et al., 2012) to remove redundant and errant points (see Spiegel et al., 2017).

We estimated composite utilization distributions (UD) for each species in two-week intervals by first calculating individual-level dynamic Brownian bridge movement model (DBBMM) surfaces (Kranstauber et al., 2012) using package Move (Kranstauber & Smolla, 2018) for R version 3.5.3 (R Core Team, 2019). This method was used because it provided better estimates of UD compared with the more traditional methods, such as kernel density analysis. DBBMM incorporates space and time into model estimates, which provides additional information about connectivity and space use and better accounts for differences in reporting rates of tags depending on deployment schedules. DBBMM also incorporates location error information and allows changes in the variance of the motion throughout the period of interest which additionally improves our estimates of the UD (Kranstauber et al., 2012). We used a margin value of 5 and window value of 15 in the model, particularly due to the short period of time we were analysing. We then calculated the weighted mean DBBMM surface (composite UD) during each two-week interval over all birds, weighting by the number of days for each animal modelled of the total number of days represented in each two-week period by all animals. The UD is a two-dimensional relative frequency distribution that describes the probability of an animal’s occurrence at any location (Van Winkle, 1975). The boundary of the animal’s home range can be found by calculating the area that encompasses 95% of the volume of the distribution of space used (Anderson, 1982). Within the home range, spatial use of the landscape can vary dramatically with certain “core use” areas being used more intensively to meet specific needs, for example reliable food sources or safe resting locations (Samuel et al., 1985).

Therefore, utilization contour levels of 50% (core use areas), 75% (intermediate use) and 95% (broader home range) were calculated for the mean UD surface and the UD was cropped to the 95% contour.

### 2.3 Exposure to offshore wind areas

We calculated spatio-temporal use of extant Lease Areas, WEAs and Call Areas (hereafter “offshore wind areas”; BOEM, 2019) by tagged birds as a proportion of offshore wind areas that were overlapped by a 95% UD home range for each species during a two-week period. Overlap was determined in R using package “sf” (Pebesma, 2018) by intersecting the 95% UD with the BOEM OCS aliquot polygons (1.2 x 1.2 km, the smallest division of leasable area, and 1/16 of a full OCS lease block, [https://catalog.data.gov/dataset/outer-continen tal-shelf-block-aliquots-atlantic-region-nad83](https://catalog.data.gov/dataset/outer-continental-shelf-block-aliquots-atlantic-region-nad83)) within each offshore wind area and assigning the value one to any intersected aliquot. To determine annual risk within each offshore wind area, we summed across all 26 two-week periods to develop the annual spatial exposure risk (max 26 in any one aliquot). We defined “persistence” as the number of biweekly periods any particular OCS aliquot was used by a species. Aliquot use was further defined as having been intersected by the 95% UD for a species during any biweekly period, and use was considered separately for each species.

Most tags used in this study transitioned to a low transmission rate during the breeding season because the original focus was on use of the mid-Atlantic region by these species, that is the non-breeding period. Thus, most tags did not provide enough transmissions within a two-week period to yield models for the breeding period. While we refer to annual exposure risk within this area, this is actually mean non-breeding season risk, but represents the majority of the annual occurrence of these species within the U.S. Atlantic OCS.

### 2.4 Statistical analysis

The goal of the analysis was to determine the influence of time and space on exposure. For the statistical analysis, exposure was calculated as the proportion of the aliquots overlapping with a UD to all aliquots in that offshore wind area. Due to non-normality in the data, we calculated the nonparametric bootstrap mean exposure (1000 resamples) and 95% confidence intervals (CI) using package Boot (Canty & Ripley, 2020; Davison & Hinkley, 1997) in R version 4.0.0 (R Core Team, 2020). Bootstrap mean temporal risk was evaluated across the annual cycle by calculating mean exposure across all 26 two-week periods, and resampling the proportion of aliquots within an offshore wind area intersected by the 95% UD over all 26 biweekly periods. Bootstrap mean spatial risk was evaluated across the study area by calculating exposure across offshore wind areas, and resampling the proportion of aliquots intersected by the 95% UD in each offshore wind area for each individual biweekly period. Samples were drawn with replacement for each replicate where the sample size is equal to the original sample (i.e. 26 biweekly periods and 27 offshore wind areas). The 95% CIs estimate variation in risk at the scale of the offshore wind area (spatial risk) or biweekly period (temporal risk). Identification of non-breeding periods (fall migration, winter, spring migration) as indicated in charts of mean temporal risk was identified by inspecting movement maps of individuals by species to find periods of directed movements from breeding to wintering areas (fall migration) and wintering to breeding areas (spring migration). Movement did occur in the winter period (particularly by Northern Gannets), but was generally less directed.

**FIGURE 1** Maps of study species persistence in the federal waters of the Atlantic Outer Continental Shelf (OCS) within the vicinity of offshore wind areas. Persistence is presented as the number of 2-week periods that a species’ 95% utilization distribution overlapped with BOEM OCS aliquot (1.2 x 1.2 km, the smallest division of leasable area, 1/16 of a full lease block), including offshore wind areas outlined in dark grey or white. Surf Scoter (a) and Red-throated Loon (b) were concentrated close to shore and near large bay mouths, while Northern Gannet (c) ranged throughout the region.
Home Range Use Persistence

Number of 2-week periods

- 1-2
- 3-4
- 5-6
- 7-8
- 9-10
- 11-12
- 13-14
- 15-16

(a) Surf Scoter
(b) Red-throated Loon
(c) Northern Gannet

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

Service Layer Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
2.5 | Limitations

We recognize several sources of potential bias in relating the movements of a sample of tracked individuals to broader populations as a result of the physical impact of marking birds with tags (Kenow et al., 2002; Lamb et al., 2020), as well as selectively capturing birds in areas accessible by small boat and in favourable conditions. We conservatively addressed the former issue by removing the first two weeks of data when birds may have experienced behavioural and/or physical effects, such as demonstrated in the first ten days by Common Loons implanted with satellite transmitters (Kenow et al., 2002). The latter consideration is more problematic for Red-throated Loons, because the majority of tags were deployed within a fairly limited area of the mid-Atlantic region, although modelled distributions based on offshore survey data indicate that we tagged birds in coastal areas of high relative density in winter (Winship et al., 2018). Northern Gannets fledglings were also tagged in Newfoundland, and Surf Scoters were tagged across a much wider geographical area along the Atlantic OCS and data suggest that the movements of these animals may reasonably represent the eastern U.S. populations (Fifield et al., 2014; Lamb et al., 2019; SDJV, 2015).

3 | RESULTS

From 2012 to 2015, we tagged 236 individuals of the three focal species from capture sites between North Carolina and New Jersey (75 Surf Scoters, 86 Red-throated Loons, 75 Northern Gannets; Table 1). An additional 109 Surf Scoters and 38 Northern Gannets tagged in prior field efforts were also included in the analysis. Due to limitations in the duration of data collected from some tags (e.g. tag failure, mortality; see Spiegel et al., 2017), however, analyses
ultimately included data from a maximum of 75 Surf Scoters, 52 Red-throated Loons and 51 Northern Gannets.

Our results indicate that Northern Gannets are likely to be exposed the most to development at offshore wind areas, followed by Red-throated Loons and then Surf Scoters (Figure 1; see Appendix S2 for details of exposure for each species, offshore wind area and two-week interval combination). No tagged Northern Gannets were exposed during the breeding season. During their fall (southerly) migration, exposure began in early October (0.13 proportion of offshore wind area aliquots were overlapped by the 95% UD) and steadily increased to its highest level by late October/early November (0.72–0.73 proportion of aliquots). During winter, their exposure varied considerably (0.23–0.68 proportion of aliquots) and increased again during spring (northerly) migration (0.54–0.81 proportion of aliquots; Figure 2c). Northern Gannets migrated northward more broadly across the Atlantic OCS with exposure to most offshore wind areas. For short periods, numbers aggregated at a few key sites inshore of the offshore wind areas, including the mouth of the Chesapeake Bay, Delaware Bay and in the New York/New Jersey Bight. Overall, Northern Gannet distributions overlapped extensively with all offshore wind areas with exposure greatest to development in areas from New York to Virginia (Figure 3c, see Appendix S3).

In contrast, Surf Scoters and Red-throated Loons exhibited patterns of exposure similar to one another (and different from Northern Gannets), using waters that were more inshore of offshore wind areas (Figure 1a,b, respectively). Surf Scoter exposure during fall migration occurred primarily at the end of October (0.50 proportion of aliquots). It then dropped to near-zero levels through the winter, when they were concentrated primarily in large bays and along the coasts (i.e. Delaware Bay, Chesapeake Bay, and Pamlico Sound). During spring, Surf Scoter exposure occurred from April to June (0.06–0.20 proportion of aliquots; Figure 2a). Red-throated Loon exposure during fall migration took place largely during the last two

**FIGURE 3** Mean annual exposure to each individual offshore wind area for each study species. Exposure is presented for each offshore wind area as the mean proportion of the 95% utilization distributions over all two-week intervals. Surf Scoter (a) and Red-throated Loon (b) had variable exposure in offshore wind areas from Massachusetts to Virginia, and little to no exposure to areas in North Carolina and South Carolina; Northern Gannet (c) was exposed to nearly all offshore wind areas. State abbreviations include: MA = Massachusetts, NY = New York, NJ = New Jersey, DE = Delaware, MD = Maryland, VA = Virginia, NC = North Carolina, SC = South Carolina, CA = Call Area; OCS, Outer Continental Shelf; WEA, Wind Energy Area.
weeks of November (0.11–0.56 proportion of aliquots) and dropped to near-zero levels through the winter when they were concentrated primarily in large bays and along the coasts (i.e. Delaware Bay, Chesapeake Bay and Pamlico Sound). In spring, Red-throated Loon exposure was concentrated in the last two weeks of April (0.43–0.59 proportion of aliquots; Figure 2b). Red-throated Loons were primarily exposed to offshore wind areas north of North Carolina during fall migration (0.0–0.56 proportion of aliquots) and spring migration (0.11–0.59 proportion of aliquots), because of their more inshore winter distributions (Figure 3b). Similarly, Surf Scoters were mostly exposed to offshore wind areas north of Maryland during fall migration (0.0–0.50 proportion of aliquots) and spring migration (0.06–0.20 proportion of aliquots; Figure 3a, see Appendix S3).

4 DISCUSSION

4.1 Spatio-temporal exposure to offshore wind areas

Our results provide a high-resolution analysis of the spatial and temporal exposure of Surf Scoters, Red-throated Loons and Northern Gannets to offshore wind development on the Atlantic OCS, which could be used to inform permitting decisions and pre- and post-construction monitoring. The results clearly indicate that Northern Gannets will experience greater exposure to offshore wind areas than Surf Scoters and Red-throated Loons. On average about 25% of offshore wind areas, during all measured periods, overlapped the 95% UD home range for Northern Gannets, compared with only 8% for Red-throated Loons and 6% for Surf Scoters.

Northern Gannets were exposed to nearly all offshore wind areas, with the greatest exposure to areas in New York through North Carolina, during both migrations and wintering months. The exposure of Northern Gannets is driven by their broad distribution across the Atlantic OCS for a considerable portion of the year (Oct–Apr; Best & Halpin, 2019; Fifield et al., 2014; Montevecchi et al., 2012; Mowbray, 2020). Northern Gannets forage opportunistically on small to mid-sized, surface-schooling fishes by plunging dives, as well as diving directly from the surface (Garthe et al., 2000; Montevecchi, 2007). During the non-breeding season, they often feed on Atlantic menhaden (Brevortia tyrannus), a small schooling forage fish, that exhibits a variable heterogeneous distribution along the Atlantic OCS, driven largely by changes in salinity, temperature and plankton (Friedland et al., 2011; Rogers & Van Den Aye, 1989). Consequently, Northern Gannets constantly shift focal foraging areas, resulting in their exposure to all of the offshore wind areas along the Atlantic OCS throughout the non-breeding season. The impact of displacement on Northern Gannet foraging opportunities and overall fitness is unknown (Goodale & Milman, 2020), but as they are highly mobile and accustomed to flying long distances in search of prey, they may be able to use alternative foraging locations.

Surf Scoters and Red-throated Loons will be exposed primarily during migration, because habitat use in winter was concentrated in shallow protected waters at the mouths of large bays, as well as in bays and the lower sections of large tributaries. Surf Scoters and Red-throated Loons exhibited a strong spatial trend, with greater exposure to offshore wind areas closer to shore and in the areas between Massachusetts and Maryland. These findings generally align with the Marine-life Data and Analysis Team (MDAT) models (version 2; Best & Halpin, 2019; Winship et al., 2018). Like Northern Gannets, the spatio-temporal exposure patterns we observed in these species may be driven by basic foraging strategy. Surf Scoters are benthic feeders that feed primarily on a variety of clams and mussels on their wintering grounds (Baldassarre, 2014), and are thus restricted to shallower coastal waters. Red-throated Loons are pursuit divers that dive from the surface to pursue small forage fishes (Eriksson, 1985; Guse et al., 2009). Their main prey is generally found in bays and coastal areas with a high chlorophyll a concentration, which are associated with increased primary productivity and, in turn, with a higher biomass of forage fishes (Kemp et al., 2005). The salinity and thermal fronts at the mouths of rivers, bays and oceanic shelf breaks, with which they are associated create an upwelling of nutrients that attract forage fish to surface waters and enhance foraging opportunities for piscivorous marine birds (Haney & McGillivary, 1985). This preference for inshore areas by Surf Scoters and Red-throated Loons leads to exposure to offshore wind areas that are in shallower water and closer to the coast. Although Red-throated Loons and Surf Scoters are less likely to be exposed to wind facilities offshore in federal waters, they have greater potential to be exposed to state-managed leases in inshore waters (<5.6 km). As the exposure of Surf Scoter and Red-throated Loon is concentrated during migrations, any avoidance behaviour is unlikely to lead to effective habitat loss, but could lead to increased energy expenditure (Fox et al., 2006).

4.2 Management implications

This study demonstrates that all three species, but Northern Gannets in particular, will be exposed to offshore wind areas and that exposure is variable through space and time. However, interpreting how observed exposure could lead to adverse effects from offshore wind energy development is challenging. Studies indicate that all three of these taxonomic groups are more vulnerable to displacement than direct mortality due to collision, because they all largely avoid offshore wind facilities (Furness et al., 2013; Garthe et al., 2017; Hartman et al., 2012; Lindeboom et al., 2011; Mendel et al., 2019; Percival, 2010; Skov, 2018; Vanermen et al., 2015), but the effects of displacement on individuals and populations are difficult to determine (Mendel et al., 2019). Many of the studies documenting avoidance have been conducted on the earliest European offshore wind developments, which involved relatively small turbines (e.g. 2.3 MW). New projects being proposed in the United States and Europe are considering turbines as large as 12 MW (GE Renewable Energy, 2019). As wind turbines become larger, greater spacing between turbines is necessary, expanding...
project footprints and increasing the distance between turbines (Elkinton et al., 2008). For example, 12 MW turbines could be spaced 1.3–1.8 km apart (Elkinton et al., 2008; GE Renewable Energy, 2019). Such an increase in spacing could change marine bird avoidance responses, either continuing to cause avoidance or providing movement corridors through wind developments (Krijgsfeld, 2014). Thus, interpreting how exposure patterns of all three species identified in our study will lead to displacement, and potential loss of foraging and wintering habitat, is unclear. Birds displaced by offshore wind developments may move to different areas with little consequence, or the displacement could have an indirect effect on populations through reduced fitness, survival and reproductive success (Langston, 2013).

Risks of adverse effects also increase as the number of offshore wind developments grow incrementally over time, adding to other threats encountered by individuals throughout their annual cycle (Goodale et al., 2019). Therefore, although the spatial extent of exposure to current offshore wind areas may be limited, associated risks would be expected to increase as more projects are built out, in both Federal and state waters. In this respect, it is important to recognize that even when seabirds do not exhibit strong spatial associations with wind energy sites, detrimental avoidance patterns may be at play (see Peschko et al., 2020).

4.3 | Conclusions

Surf Scoters, Red-throated Loons and Northern Gannets will be exposed to offshore wind development in the Atlantic OCS. The extent of exposure varies by species and may be limited by their general use of shallower, inshore waters on migration and throughout the winter. These insights into the risk of exposure to potential offshore wind development by diving birds could be used to inform development permitting and monitoring decisions. Specifically, the results from this study can (a) provide a pre-construction baseline of exposure to the offshore wind areas in the Atlantic OCS, (b) inform risk assessments for each offshore wind area, (c) identify the primary periods when birds are more likely to be exposed and (d) support prioritizing post-construction monitoring efforts. Future research should focus on whether displacement actually reduces foraging opportunities to the point that it would affect an individual’s fitness.

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PEER REVIEW

The peer review history for this article is available at https://publon.com/publon/10.1111/ddi.13168.

DATA AVAILABILITY STATEMENT

Tracking data are currently archived at Movebank (www.movebank.org), and available in a series of summary maps on the Northeast Ocean Data Portal (www.northeastoceandata.org).

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**BIOSKETCH**

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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