Received: 9 January 2020 | Revised: 5 August 2020 | Accepted: 9 September 2020

DOI: 10.1111/ddi.13168

BIODIVERSITY RESEARCH

Diversity and Distributions WILEY

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

Iain J. Stenhouse[1] | **Alicia M. Berlin**[2] | **Andrew T. Gilbert**[1] | **M. Wing Goodale**[1] | **Carrie E. Gray**[3] | **William A. Montevecchi**[4] | **Lucas Savoy**[1] | **Caleb S. Spiegel**[5]

[1]Biodiversity Research Institute, Portland, ME, USA

[2]Patuxent Wildlife Research Center, U.S. Geological Survey, Laurel, MD, USA

[3]School of Biology and Ecology, University of Maine, Orono, ME, USA

[4]Memorial University of Newfoundland, St. John's, NL, Canada

[5]Division of Migratory Birds, U.S. Fish & Wildlife Service, Hadley, MA, USA

Correspondence
Iain J. Stenhouse, Biodiversity Research Institute, Portland, ME, USA.
Email: iain.stenhouse@briloon.org

Funding information
Bureau of Ocean Energy Management; U.S. Department of Energy; U.S. Fish & Wildlife Service; Sea Duck Joint Venture; Bailey Foundation.

Editor: Alice Hughes

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 CO_2 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.

KEYWORDS
Atlantic Outer Continental Shelf, diving birds, Northern Gannet, offshore wind energy, Red-throated Loon, spatial use, Surf Scoter, wildlife tracking

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 (Rizzoloet 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; Vanermen 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

TABLE 1 Deployment years, locations and sample size of each attachment method for diving bird species tagged in this study

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/Virginia	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/Virginia	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/Virginia	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

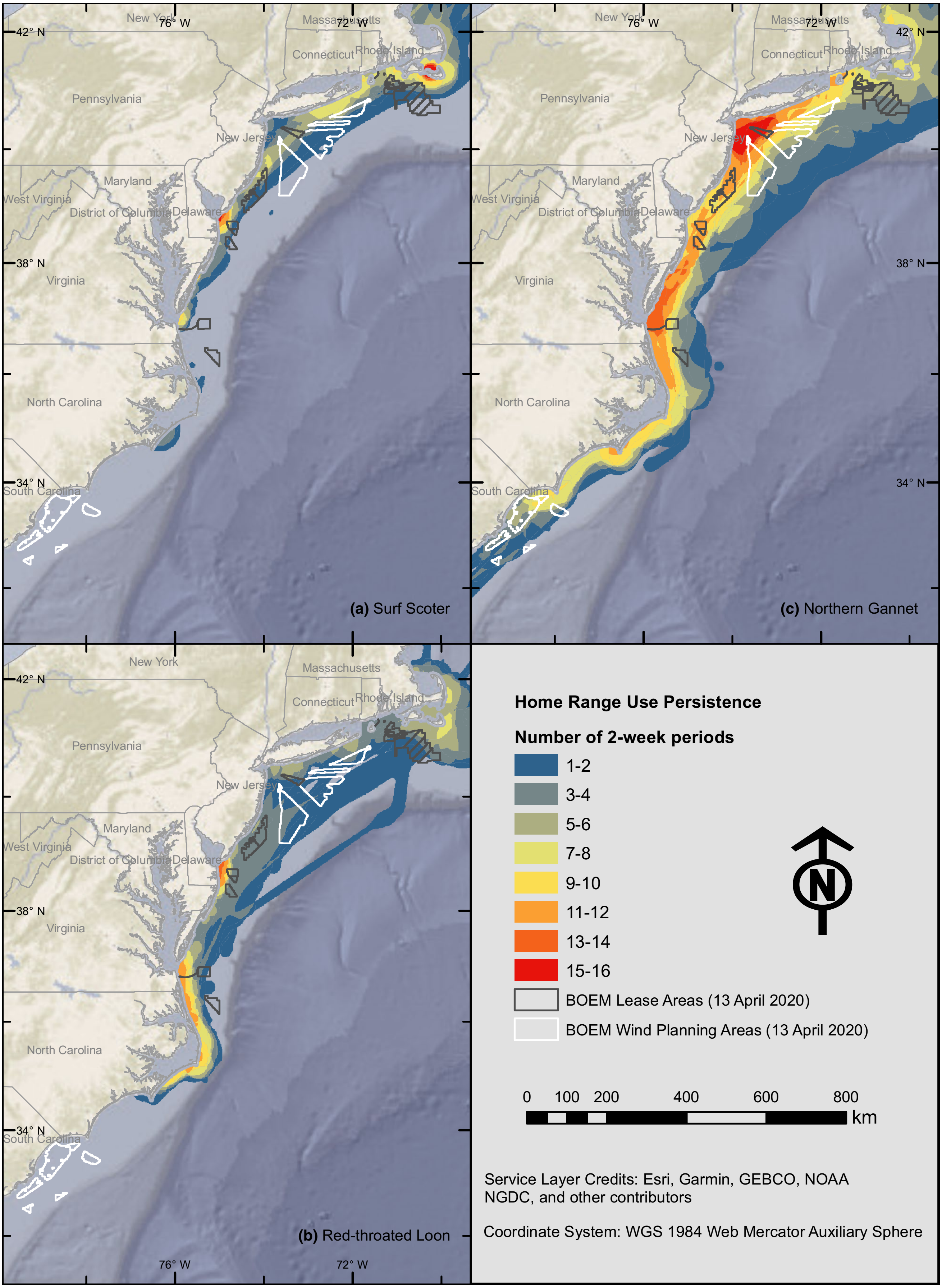
We calculated spatio-temporal use of extant Lease Areas, WEAs and Call Areas(hereafter "offshore wind areas"; BOEM, 2019) by tagged birds as a proportion of offshore wind areas that were overlapped by a 95% UD home range for each species during a two-week period. Overlap was determined in R using package "sf" (Pebesma, 2018) by intersecting the 95% UD with the BOEM OCS aliquot polygons (1.2 × 1.2 km, the smallest division of leasable area, and 1/16 of a full OCS lease block, https://catalog.data.gov/dataset/outer-continetal-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 × 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


(a) Surf Scoter
(b) Red-throated Loon
(c) Northern Gannet
76° W
72° W
42° N
38° N
34° N
New York
Massachusetts
Connecticut
Rhode Island
Pennsylvania
New Jersey
Maryland
West Virginia
District of Columbia
Delaware
Virginia
North Carolina
South Carolina
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
BOEM Lease Areas (13 April 2020)
BOEM Wind Planning Areas (13 April 2020)
N
0
100
200
400
600
800
km
Service Layer Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors
Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

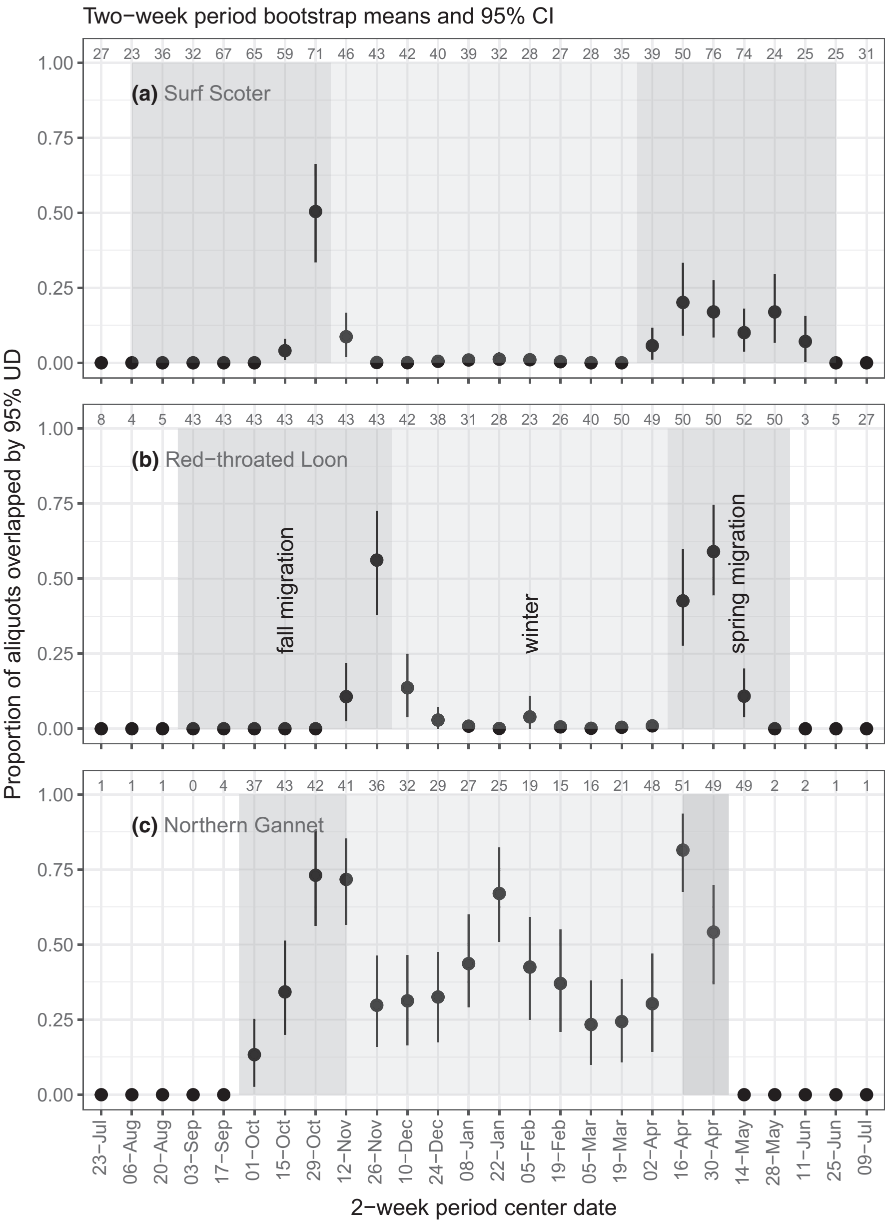


FIGURE 2 Mean exposure by date to any offshore wind areas for each study species. Exposure is presented in two-week intervals as the proportion of the aliquots overlapping with a 95% UD to all aliquots in offshore wind areas. Sample sizes (*n*), displayed along the top of each panel, represent the number of individual birds providing data in each 2-week period. Surf Scoter (a) and Red-throated Loon (b) were exposed primarily during migration and had little exposure during the winter; Northern Gannet (c) was consistently exposed during the migration and throughout the winter period

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

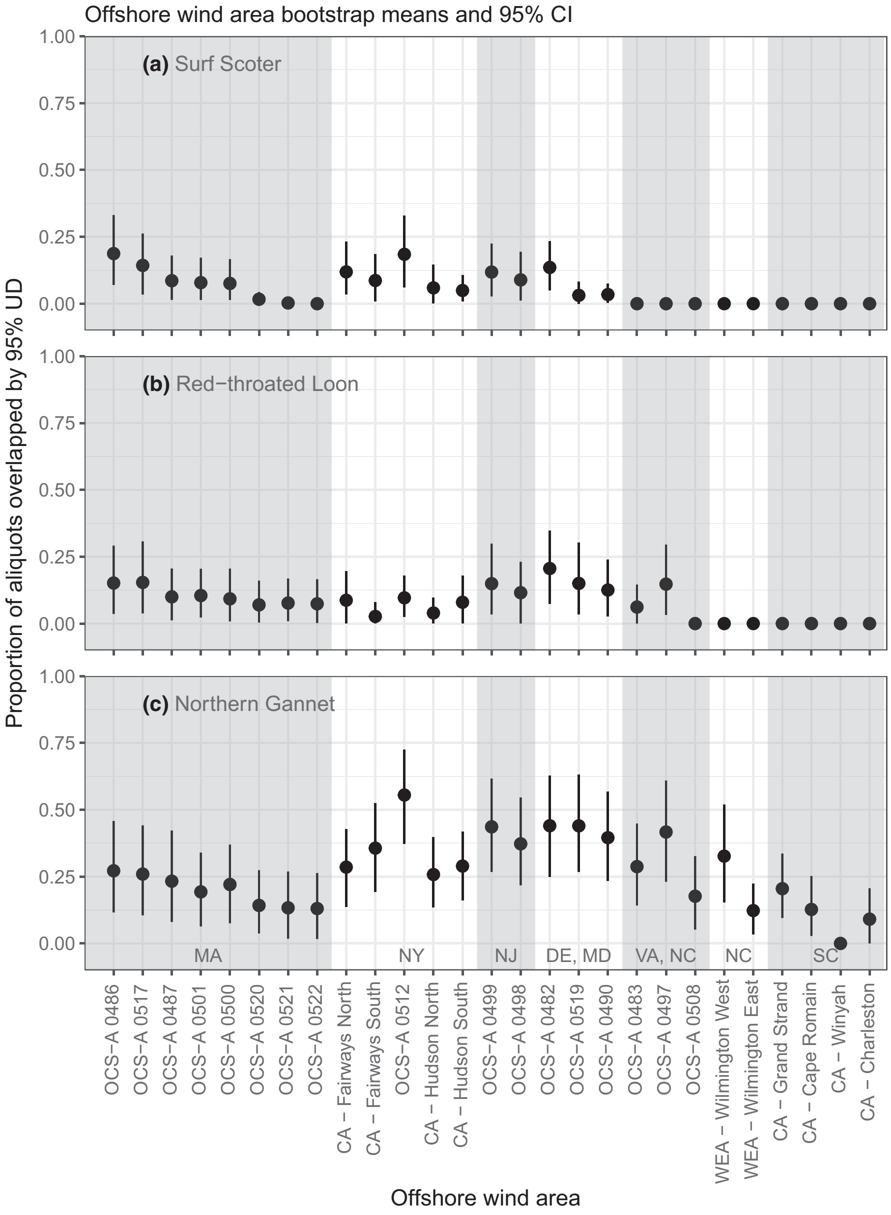


FIGURE 3 Mean annual exposure to each individual offshore wind area for each study species. Exposure is presented for each offshore wind area as the mean proportion of the 95% utilization distributions over all two-week intervals. Surf Scoter (a) and Red-throated Loon (b) had variable exposure in offshore 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 (*Brevoortiatyrannus*), 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 Ayle, 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 (Krijgsveld, 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.

ACKNOWLEDGEMENTS

This project was funded by the Bureau of Ocean Energy Management (BOEM) through IAA #M12PG00005 with the U.S. Fish and Wildlife Service (USFWS), with the additional support of the U.S. Department of Energy (DOE), the Sea Duck Joint Venture (SDJV), the Bailey Foundation and USFWS. We are indebted to many field assistants who conducted work in gruelling field conditions, veterinarians for their avian care and scientists who provided insight and technical support. Special thanks go to S. Ford, G. Olsen, J. Fiely, C. Anderson, C. Burke, J. Woehr, S. Johnston, D. Howell, T. Bowman and S. Gilliland. Partners in the SDJV graciously allowed us to use their tracking data as part of our analyses. Throughout this study, all field efforts (including capture, handling and tag deployment) were carried out under approved federal and state permits, and all applicable national and institutional guidelines for the care and use of animals were followed. We acknowledge two anonymous reviewers whose comments improved the manuscript. The views and conclusions contained in this paper are those of the authors and should not be interpreted as representing opinions or policies of the USFWS, BOEM or DOE. Mention of trade names or commercial products does not constitute endorsement by the U.S. government.

PEER REVIEW

The peer review history for this article is available at https://publons.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).

ORCID

Iain J. Stenhouse https://orcid.org/0000-0003-3614-9862
Carrie E. Gray https://orcid.org/0000-0001-9721-8601

REFERENCES

Allen, A. M., & Singh, N. (2016). Linking movement ecology with wildlife management and conservation. *Frontiers in Ecology and Evolution*, *3*, 155. https://doi.org/10.3389/fevo.2015.00155

Allison, T. D., Jedrey, E., & Perkins, S. (2008). Avian issues for offshore wind development. *Marine Technology Society Journal*, *42*, 28–38. https://doi.org/10.4031/002533208786829115

Anderson, D. J. (1982). The home range: A new nonparametric estimation technique. *Ecology*, *63*, 103–112. https://doi.org/10.2307/1937036

Anderson, E. M., Dickson, R. D., Lok, E. K., Palm, E. C., Savard, J. L., Bordage, D., & Reed, A. (2020). Surf Scoter (*Melanitta perspicillata*), version 1.0. In P. G. Rodewald (Ed.), *Birds of the World*, Ithaca, NY: Cornell Lab of Ornithology.

Aquarone, M. C., & Adams, S. (2018). *XIX-61 Northeast U.S. Continental Shelf: LME #7. Large Marine Ecosystems of the World*. http://lme.edc.uri.edu/index.php/lme-briefs/65-northeast-u-s-continental-shelf-lme-7 (accessed 17 July 2018).

Argos (2019). *Wildlife monitoring*. http://www.argos-system.org/applications-argos/wildlife-monitoring/ (accessed 07 June 2019).

Bailey, H., Brookes, K. L., & Thompson, P. M. (2014). Assessing environmental impacts of offshore wind farms: Lessons learned and recommendations for the future. *Aquatic Biosystems*, *10*, 8. https://doi.org/10.1186/2046-9063-10-8

Baldassarre, G. A. (2014). *Ducks, geese, and swans of North America* (vol. *2*, p. 466). Baltimore, MD: John Hopkins University Press.

Best, B. D., & Halpin, P. N. (2019). Minimizing wildlife impacts for offshore wind energy development: Winning tradeoffs for seabirds in space and cetaceans in time. *PLoS One*, *14*(5), e0215722. https://doi.org/10.1371/journal.pone.0215722

BOEM (Bureau of Ocean Energy Management) (2017). *Outer Continental Shelf Renewable Energy Leases Map Book*. https://www.boem.gov/Renewable-Energy-Lease-Map-Book/ (accessed 12 May 2017).

BOEM (Bureau of Ocean Energy Management) (2019). *State Activities*. https://www.boem.gov/Renewable-Energy-State-Activities/ (accessed 24 January 2019).

Bruckner, T., Bashmakov, I. A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H. B., Riahi, K., Strachan, N., Wiser, N., & Zhang, R. (2014). Energy systems. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, … J. C. Minx (Eds.), *Climate Change 2014: Mitigation of Climate Change* (pp. 511–598). Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press (1434 pp).

Canty, A., & Ripley, B. (2020). *boot: Bootstrap R (S-Plus) Functions*. R package version 1.3-25.

Cook, A. S. C. P., Johnston, A., Wright, L. J., & Burton, N. H. K. (2012). *A review of flight heights and avoidance rates of birds in relation to offshore wind farms* (p. 61). Thetford, UK: British Trust for Ornithology.

Davison, A. C., & Hinkley, D. V. (1997). *Bootstrap methods and their applications* (p. 592). Cambridge, UK: Cambridge University Press.

Desholm, M., & Kahlert, J. (2005). Avian collision risk at an offshore wind farm. *Biology Letters*, *2005*(1), 296–298. https://doi.org/10.1098/rsbl.2005.0336

Dierschke, V., Furness, R. W., & Garthe, S. (2016). Seabirds and offshore wind farms in European waters: Avoidance and attraction. *Biological Conservation*, *202*, 59–68. https://doi.org/10.1016/j.biocon.2016.08.016

Douglas, D. C., Weinzierl, R., C. Davidson, S., Kays, R., Wikelski, M., & Bohrer, G. (2012). Moderating Argos location errors in animal tracking data. *Methods in Ecology and Evolution*, *3*, 999–1007. https://doi.org/10.1111/j.2041-210X.2012.00245.x

Drewitt, A. L., & Langston, R. H. W. (2006). Assessing impacts of wind farms on birds. *Ibis*, *148*, 29–42.

Elkinton, C., Manwell, J., & McGowan, J. (2008). Algorithms for offshore wind farm layout optimization. *Wind Engineering*, *32*, 67–84. https://doi.org/10.1260/030952408784305877

Eriksson, M. O. G. (1985). Prey detectability for fish-eating birds in relation to fish density and water transparency. *Ornis Scandinavica*, *16*, 1–7. https://doi.org/10.2307/3676567

Fifield, D. A., Montevecchi, W. A., Garthe, S., Robertson, G. J., Kubetzki, U., & Rail, J.-F. (2014). Migratory tactics and wintering areas of Northern Gannets (*Morusbassanus*) breeding in North America. *Ornithological Monographs*, *79*, 1–63.

Ford, S. L., Olsen, G. H., & Berlin, A. M. (2017). Captive Care and Surgery of Diving Birds Fitted with PTTs. In C. Spiegel et al *Determining fine-scale use and movement patterns of diving bird species in federal waters of the Mid- Atlantic United States Using Satellite Telemetry* (pp. 152–179). OCS Study BOEM 2017–069. Sterling, VA: Bureau of Ocean Energy Management, 293 pp.

Fox, A. D., Desholm, M., Kahlert, J., Christensen, T. J., & Krag Petersen, I. B. (2006). Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds. *Ibis*, *148*, 129–144. https://doi.org/10.1111/j.1474-919X.2006.00510.x

Friedland, K. D., Lynch, P. D., & Gobler, C. J. (2011). Time series mesoscale response of Atlantic menhaden (*Brevoortiatyrannus*) to variation in plankton abundances. *Journal of Coastal Research*, *27*, 1148–1158.

Furness, R. W., Wade, H. M., & Masden, E. A. (2013). Assessing vulnerability of marine bird populations to offshore wind farms. *Journal of Environmental Management*, *119*, 56–66. https://doi.org/10.1016/j.jenvman.2013.01.025

Garthe, S., Benvenuti, S., & Montevecchi, W. A. (2000). Pursuit-plunging by gannets. *Proceedings of the Royal Society of London Series B: Biological Sciences*, *267*, 1717–1722.

Garthe, S., Markones, N., & Coleman, A. (2017). Possible impacts of offshore wind farms on seabirds: A pilot study in Northern Gannets in the southern North Sea. *Journal of Ornithology*, *158*, 345–349. https://doi.org/10.1007/s10336-016-1402-y

GE Renewable Energy (2019). *Haliade-X Offshore Wind Turbine Platform*. https://www.ge.com/renewableenergy/wind-energy/turbines/haliade-x-offshore-turbine (accessed 11 Jan 2019).

Goodale, M. W., & Milman, A. (2016). Cumulative adverse effects of offshore wind energy development on wildlife. *Journal of Environmental Planning and Management*, *59*, 1–21. https://doi.org/10.1080/09640568.2014.973483

Goodale, M. W., & Milman, A. (2020). Assessing the cumulative exposure of Northern Gannets to offshore wind farms. *Wildlife Society Bulletin*, *44*, 252–259. https://doi.org/10.1002/wsb.1087

Goodale, M. W., Milman, A., & Griffin, C. R. (2019). Assessing cumulative adverse effects of offshore wind development on seabird foraging guilds along the East Coast of the United States. *Environmental Research Letters*, *14*(7), 74018. https://doi.org/10.1088/1748-9326/ab205

Guse, N., Garthe, S., & Schirmeister, B. (2009). Diet of Red-throated Divers (*Gaviastellata*) reflects the seasonal availability of Atlantic Herring (*Clupea harengus*) in the southwestern Baltic Sea. *Journal of Sea Research*, *62*, 68–275. https://doi.org/10.1016/j.seares.2009.06.006

Haney, J. C., & McGillivary, P. A. (1985). Midshelf fronts in the South Atlantic Bight and their influence on seabird distribution and seasonal abundance. *Biological Oceanography*, *3*, 401–430.

Hartman, J. C., Krijgsveld, K. L., Poot, M. J. M., Fijn, R. C., Leopold, M. F., & Dirksen, S. (2012). *Effects on birds of offshore wind farm Egmond aan Zee (OWEZ). An overview and integration of insights obtained*. Report 12–005. Culemborg, The Netherlands: Bureau Waardenburg, , 146 p.

Heinänen, S., Žydelis, R., Kleinschmidt, B., Dorsch, M., Burger, C., Morkūnas, J., Quillfeldt, P., & Nehls, G. (2020). Satellite telemetry and digital aerial surveys show strong displacement of Red-throated Divers (*Gaviastellata*) from offshore wind farms. *Marine Environmental Research*, *160*, 104989. https://doi.org/10.1016/j.marenvres.2020.104989

Hüppop, O., Dierschke, J., Exo, K., Fredrich, E., & Hill, R. (2006). Bird migration studies and potential collision risk with offshore wind turbines. *Ibis*, *148*, 90–109. https://doi.org/10.1111/j.1474-919X.2006.00536.x

Kemp, W. M., Boynton, W. R., Adolf, J. E., Boesch, D. F., Boicourt, W. C., Brush, G., Cornwell, J. C., Fisher, T. R., Glibert, P. M., Hagy, J. D., Harding, L. W., Houde, E. D., Kimmel, D. G., Miller, W. D., Newell, R., Roman, M. R., Smith, E. M., & Stevenson, J. C. (2005). Eutrophication of Chesapeake Bay: Historical trends and ecological interactions. *Marine Ecology Progress Series*, *303*, 1–29. https://doi.org/10.3354/meps303001

Kenow, K., Meyer, M., Evers, D., Douglas, D., & Hines, J. (2002). Use of satellite telemetry to identify Common Loon migration routes, staging areas and wintering range. *Waterbirds*, *25*(4), 449–458. https://doi.org/10.1675/1524-4695(2002)025[0449:UOSTTI]2.0.CO;2

Korschgen, C., Kenow, K., Gendron-Fitzpatrick, A., Green, W., & Dein, F. (1996). Implanting intra-abdominal radiotransmitters with external whip antennas in ducks. *Journal of Wildlife Management*, *60*, 132–137. https://doi.org/10.2307/3802047

Kranstauber, B., Kays, R., Lapoint, S. D., Wikelski, M., & Safi, K. (2012). A dynamic Brownian bridge movement model to estimate utilization distributions for heterogeneous animal movement. *Journal of Animal Ecology*, *81*, 738–746. https://doi.org/10.1111/j.1365-2656.2012.01955.x

Kranstauber, B., & Smolla, M. (2018). *Move: Visualizing and analyzing animal track data*. R package version 3.1.0. https://rdrr.io/cran/move/ (accessed 24 January 2019).

Krijgsveld, K. L. (2014). *Avoidance behavior of birds around offshore wind farms: Overview of knowledge including effects of configuration* (p. 35). Bureau Waardenburg bv.

Krijgsveld, K. L., Fijn, R. C., Japink, M., van Horssen, P. W., Heunks, C., Collier, M. P., Poot, M. J. M., Beuker, D., & Dirksen, S. (2011). *Effect studies offshore wind farm Egmond aan Zee: Flux, flight altitude and behaviour of flying birds*. Final Report to NoordzeeWind. Culemborg, The Netherlands: Bureau Waardenburg, 328 pp.

Lamb, J. S., Paton, P. W. C., Osenkowski, J. E., Badzinski, S. S., Berlin, A. M., Bowman, T., Dwyer, C., Fara, L. J., Gilliland, S. G., Kenow, K., Lepage, C., Mallory, M. L., Olsen, G. H., Perry, M. C., Petrie, S. A., Savard, J.-P., Savoy, L., Schummer, M., Spiegel, C. S., & McWilliams, S. R. (2019). Spatially explicit network analysis reveals multi-species annual cycle movement patterns of sea ducks. *Ecological Applications*, *29*, e01919. https://doi.org/10.1002/eap.1919

Lamb, J. S., Paton, P. W. C., Osenkowski, J. E., Badzinski, S. S., Berlin, A. M., Bowman, T., Dwyer, C., Fara, L. J., Gilliland, S. G., Kenow, K., LePage, C., Mallory, M. L., Olsen, G. H., Perry, M. C., Petrie, S. A., Savard, J.-P. L., Savoy, L., Schummer, M., Spiegel, C. S. & McWilliams, S. R. (2020). Evaluating short- and long-term effects of implanted satellite transmitters on sea duck movement and behavior. *The Condor: Ornithological Applications*, *122*, duaa029. https://doi.org/10.1093/condor/duaa029

Langston, R. H. W. (2013). Birds and wind projects across the pond: A UK perspective. *Wildlife Society Bulletin*, *37*, 5–18. https://doi.org/10.1002/wsb.262

Larsen, J. K., & Guillemette, M. (2007). Effects of wind turbines on flight behavior of wintering Common Eiders: Implications for habitat use and collision risk. *Journal of Applied Ecology*, *44*, 516–522.

Leonhard, S. B., Pederse, J., Grøn, P. N., Skov, H., Jansen, J., Topping, C., & Petersen, I. K. (2013). Wind farms affect common scoter and red-throated diver behaviour. In *Danish Offshore Wind, Key Environmental Issues – A Follow-Up* (pp. 70–93). The Environmental Group: The Danish Energy Agency, The Danish Nature Agency, DONG Energy and Vattenfall. https://ens.dk/sites/ens.dk/files/Vindenergi/havvindmoellebog_web1.pdf.

Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S., Daan, R., Fijn, R. C., de Haan, D., Dirksen, S., van Hal, R., Hille Ris Lambers, R., ter Hofstede, R., Krijgsveld, K. L., Leopold, M., & Scheidat, M. (2011). Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters*, *6*, 35101. https://doi.org/10.1088/1748-9326/6/3/035101

MANEM (2006). *Waterbird conservation plan for the Mid-Atlantic/New England/Maritimes Region: 2006–2010* (p. 44). Unpublished draft report. Monomet, MA: MANEM Waterbird Working Group, Manomet Center for Conservation Science.

Mendel, B., Schwemmer, P., Peschko, V., Müller, S., Schwemmer, H., Mercker, M., & Garthe, S. (2019). Operational offshore wind farms and associated ship traffic cause profound changes in distribution patterns of Loons (*Gavia* spp.). *Journal of Environmental Management*, *231*, 429–438. https://doi.org/10.1016/j.jenvman.2018.10.053

Montevecchi, W. A. (2007). Binary responses of Northern Gannets to changing food web and oceanographic conditions. *Marine Ecology Progress Series*, *352*, 213–220.

Montevecchi, W., Fifield, D., Burke, C., Garthe, S., Hedd, A., Rail, J.-F., & Robertson, G. (2011). Tracking long-distance migration to assess marine pollution impact. *Biology Letters*, *8*, 218–221.

Montevecchi, W. A., Hedd, A., McFarlane-Tranquilla, L., Fifield, D. A., Burke, C. M., Regular, P. M., Davoren, G. K., Garthe, S., Robertson, G. J., & Phillips, R. A. (2012). Tracking seabirds to identify ecologically important and high risk marine areas in the western North Atlantic. *Biological Conservation*, *156*, 62–71. https://doi.org/10.1016/j.biocon.2011.12.001

Mowbray, T. B. (2020). Northern Gannet (*Morus bassanus*), version 1.0. In S. M. Billerman (Ed.), *Birds of the World*. Ithaca, NY: Cornell Lab of Ornithology.

Mulcahy, D. M., & Esler, D. (1999). Surgical and immediate post-release mortality of Harlequin Ducks (*Histrionicus histrionicus*) implanted with abdominal radio transmitters with percutaneous antennae. *Journal of Zoo and Wildlife Medicine*, *30*, 397–401.

Musial, W., Heimiller, D., Beiter, P., Scott, G., & Draxl, C. (2016). *Offshore Wind Energy Resource Assessment for the United States*. NREL Technical Report NREL/TP-5000-66599. National Renewable Energy Laboratory, Golden, CO. 88 pp.

Nisbet, I. C. T., Veit, R. R., Auer, S. A., & White, T. P. (2013). *Marine birds of the Eastern United States and the Bay of Fundy: Distribution, numbers, trends, threats, and management*. Nuttall Ornithological Monographs Series, No. 29 (198 pp). Cambridge, MA: Nuttall Ornithological Club.

Ørsted (2019). *Block Island Wind Farm*. https://us.orsted.com/Wind-projects (accessed 05 December 2019).

Pebesma, E. (2018). Simple features for R: Standardized support for spatial vector data. *The R Journal*, , *10*(1), 439. https://doi.org/10.32614/RJ-2018-009

Percival, S. (2010). *Kentish Flats Offshore Wind Project: Diver Surveys 2009–10* (31 pp.). Report commissioned by Vattenfall Wind Power. Ecology Consulting, .

Peschko, V., Mercker, M., & Garthe, S. (2020). Telemetry reveals strong effects of offshore wind farms on behavior and habitat use of Common Guillemots (*Uriaaalge*) during the breeding season. *Marine Biology*, *167*, 118. https://doi.org/10.1007/s00227-020-03735-5

Petersen, I. K., & Fox, A. D. (2007). *Changes in bird habitat utilisation around the Horns Rev 1 Offshore Wind farm, with Particular Emphasis on Common Scoter* (40 pp). : National Environmental Research Institute, University of Aarhus.

Phillips, E. M., Horne, J. K., Zamon, J. E., Felis, J. J., & Adams, J. (2019). Does perspective matter? A case study comparing Eularian and Lagrangian estimates of Common Murre (*Uriaaalge*) distributions. *Ecology and Evolution*, *9*, 4805–4819.

R Core Team (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. http://www.r-project.org.

R Core Team (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. http://www.r-project.org.

Rizzolo, D. J., Gray, C. E., Schmutz, J. A., Barr, J. F., Eberl, C., & McIntyre, J. W. (2020). Red-throated Loon (*Gavia stellata*), version 2.0. In P. G. Rodewald, & B. K. Keeney (Eds.), *Birds of the World*, Ithaca, NY: Cornell Lab of Ornithology.

Rogers, S. G., & Van Den Ayle, M. J. (1989). *Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Mid-Atlantic) – Atlantic Menhaden*. U.S. Fish & Wildlife Service Biological Report 82 (11.108). U.S. Army Corps of Engineers Technical Report EL-82-4. Vicksburg, MS: U.S. Army Corps of Engineers, 23 pp.

Samuel, M. D., Pierce, D. J., & Garton, E. O. (1985). Identifying areas of concentrated use within the home range. *Journal of Animal Ecology*, *54*, 711–719. https://doi.org/10.2307/4373

Schreiber, E. A., & J. Burger (Eds.) (2001). *Biology of marine birds* (740 pp.). Boca Raton, FL: CRC Press.

Schuster, S., Bulling, L., & Köppel, J. (2015). Consolidating the state of knowledge: A synoptical review of wind energy's wildlife effects. *Environmental Management*, *56*, 300–331. https://doi.org/10.1007/s00267-015-0501-5

SDJV (Sea Duck Joint Venture) (2010). *How we catch sea ducks*. https://seaduckjv.org/pdf/to_catch_a_sea_duck.pdf (accessed 22 January 2019).

SDJV (Sea Duck Joint Venture) (2015). *Atlantic and Great Lakes Sea Duck Migration Study: Progress Report* – June 2015. http://seaduckjv.org/science-resources/atlantic-and-great-lakes-sea-duck-migration-study/ (accessed 24 January 2019).

Skov, H., Heinänen, S., Norman, T., Ward, R. M., Méndez-Roldán, S., & Ellis, I. (2018). *ORJIP Bird Collision and Avoidance Study*. Final Report – April 2018. London, UK: The Carbon Trust, 247 pp.

Snyder, B., & Kaiser, M. J. (2009). Ecological and economic cost-benefit analysis of offshore wind energy. *Renewable Energy*, *34*, 1567–1578. https://doi.org/10.1016/j.renene.2008.11.015

Spiegel, C. S., Berlin, A. M., Gilbert, A. T., Gray, C. O., Montevecchi, W. A., Stenhouse, I. J., Ford, S. L., Olsen, G. H., Fiely, J. L., Savoy, L., Goodale,

M. W., & Burke, C. M. (2017). *Determining fine- scale use and movement patterns of diving bird species in federal waters of the Mid- Atlantic United States Using Satellite Telemetry*. Final Report, OCS Study BOEM 2017–069. Sterling, VA: U.S. Dept. of the Interior, Bureau of Ocean Energy Management, 293 pp.

Stenhouse, I. J., Montevecchi, W. A., Gray, C. E., Gilbert, A. T., Burke, C. M., & Berlin, A. M. (2017). Occurrence and Migration of Northern Gannets Wintering in Offshore Waters of the Mid-Atlantic United States. In *Determining fine- scale use and movement patterns of diving bird species in Federal Waters of the Mid- Atlantic United States Using Satellite Telemetry* (C. Spiegel et al) OCS Study BOEM 2017-069 (pp. 4–59). Sterling, VA: Bureau of Ocean Energy Management, 293 pp.

USFWS (U.S. Fish and Wildlife Service) (2008). *Final biological opinion*, Cape Wind Associates, LLC, Wind Energy Project, Nantucket Sound, Massachusetts. Unpublished Report. Concord, NH: U.S. Fish and Wildlife Service, New England Field Office, (97 pp). https://www.epa.gov/sites/production/files/2015-08/documents/cape-wind-fws-noaa-opinion.pdf (accessed 22 Nov 2019).

Van Winkle, W. (1975). Comparison of several probabilistic home-range models. *Journal of Wildlife Management*, *39*, 118–123. https://doi.org/10.2307/3800474

Vanermen, N., Onkelinx, T., Courtens, W., Van de walle, M., Verstraete, H., & Stienen, E. W. M. (2015). Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea. *Hydrobiologia*, *756*, 51–61. https://doi.org/10.1007/s10750-014-2088-x

Wade, H. M., Masden, E. A., Jackson, A. C., & Furness, R. W. (2016). Incorporating data uncertainty when estimating potential vulnerability of Scottish seabirds to marine renewable energy developments. *Marine Policy*, *70*, 108–113. https://doi.org/10.1016/j.marpol.2016.04.045

Warden, M. L. (2010). Bycatch of wintering Common and Red-throated Loons in gillnets off the USA Atlantic coast, 1996–2007. *Aquatic Biology*, *10*, 167–180.

Whitworth, D. L., Takekawa, J. Y., Carter, H. R., & McIver, W. R. (1997). A night-lighting technique for at-seacapture of Xantus' Murrelets. *Colonial Waterbirds*, *20*, 525–531. https://doi.org/10.2307/1521603

WindEurope (2020). *Offshore wind in Europe: Key trends and statistics 2019*. Brussels, Belgium: WindEurope, 20 pp.

Winship, A. J., Kinlan, B. P., White, T. P., Leirness, J. B., & Christensen, J. (2018). *Modeling At-Sea Density of Marine Birds to Support Atlantic Marine Renewable Energy Planning: Final Report*, OCS Study BOEM 2018–010. Sterling, VA: U.S. Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, 76 pp.

BIOSKETCH

Iain Stenhouse is the Director of the Marine Bird Program at the Biodiversity Research Institute. See his webpage for more information: http://www.briloon.org/about-us/bri-staff/science-directors/iain-stenhouse-ph-d. He is part of a broad research effort, including NGOs, academics, and government agencies, dedicated to improving our understanding of the interactions between marine birds and offshore wind development on the U.S. Outer Continental Shelf.

Author contributions: All authors contributed to the study's conception and design, wrote sections of the manuscript, updated manuscript drafts and provided final approval for publication. A.M.B., C.E.G., L.S. and W.A.M. conducted the bulk of the fieldwork. A.T.G., C.E.G., A.M.B., I.J.S., and W.A.M. conducted the analyses. A.T.G. and I.J.S. prepared the figures. C.S.S. facilitated and coordinated the project.

SUPPORTING INFORMATION

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

How to cite this article: Stenhouse IJ, Berlin AM, Gilbert AT, et al. Assessing the exposure of three diving bird species to offshore wind areas on the U.S. Atlantic Outer Continental Shelf using satellite telemetry. *Divers Distrib* 2020;00:1–12. https://doi.org/10.1111/ddi.13168