12 July 2021
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Oceanic Records of North American Bats and Implications for Offshore Wind Energy Development in the United States

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ABSTRACT Offshore wind energy is a growing industry in the United States, and renewable energy from offshore wind is estimated to double the country's total electricity generation. There is growing concern that land-based wind development in North America is negatively impacting bat populations, primarily long-distance migrating bats, but the impacts to bats from offshore wind energy is unknown. Bats are associated with the terrestrial environment, but have been observed over the ocean. In this review, we synthesize historic and contemporary accounts of bats observed and acoustically recorded offshore over North American waters to ascertain the spatial and temporal distribution of bats flying offshore. We integrate these records with studies of offshore bats in Europe and of bat behavior at land-based wind energy studies to

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examine how offshore wind development could impact North American bat populations. We find that most offshore bat records are of long-distance migrating bats and records occur during autumn migration, the period of highest fatality rates for long-distance migrating bats at land-based wind facilities in North America. We summarize evidence that bats may be attracted to offshore turbines for roosting and foraging opportunities, potentially increasing their risk of collision, but that higher wind speeds offshore can potentially reduce the amount of time that bats are exposed to risk. We identify knowledge gaps and hypothesize that a combination of mitigation strategies may be the most effective approach for minimizing impacts to bats and maximizing offshore energy production.

KEY WORDS Atlantic Ocean, bats, North America, offshore, wind energy, wind turbines.

The electricity potential from offshore wind in the United States is estimated to be more than 2,000 gigawatts, roughly twice the nation's current total generation (Musail et al. 2016). Two wind farms are now in operation off the coasts of Rhode Island and Virginia (Figure 1), while 29 offshore wind farms are in varying stages of development in the United States (AWEA 2020a), with a projected build-out of 30 gigawatts of offshore energy by the year 2030. The adverse effects of offshore wind generation on wildlife are generally acknowledged to be low relative to those of conventional electricity generation technologies (Gibson et al. 2017; Allison et al. 2019). However, adverse impacts are still possible, and understanding the ecological significance of these effects is necessary for responsible development of offshore wind energy resources.

There is growing concern that North American bat populations are being adversely impacted by land-based wind development. An estimated 600,000 to 888,000 bats died from interactions with land-based wind turbines in the United States during 2012 (Hayes 2013; Smallwood 2013), and installed wind power capacity has nearly doubled over the following eight years (Orrell et al. 2013; AWEA 2020b). Some North American species, such as the hoary bat (*Lasiurus cinereus*), can potentially be at risk of population decline or extinction due to wind energy development (Frick et al. 2017; EPRI 2020). Bat fatalities are mainly due to collisions with moving turbine blades (Grodsky et al. 2011; Rollins et al. 2012; Lawson et al. 2020), though the underlying reasons for why bats approach turbines are still largely unknown (Cryan and Barclay 2009; Barclay et al. 2017). To date, post-construction monitoring studies of land-based wind energy facilities in the United States indicate: 1) long-distance migrating species (e.g., hoary bat, eastern red bat [*Lasiurus borealis*], and silver-haired bat [*Lasionycteris noctivagans*]) compose approximately 72% of reported bats killed; 2) the majority of fatalities occur during the autumn migration season (August and September); and 3) most fatalities occur on nights with relatively low wind speeds (e.g., < 6.0 meters/second [m/s]; Arnett et al. 2008; AWWI 2020).

Bats are primarily associated with terrestrial environments, yet some species are known to forage or migrate offshore. In Europe, field observations and band returns have shown that some species migrate seasonally across the Baltic and North Seas between the European continent and either Sweden or the United Kingdom, and some non-migratory species forage over water far from shore (Ahlén et al. 2007, 2009; Lagerveld et al 2014; Hüppop and Hill 2016; Moores 2017). In general, bats have been observed flying over large bodies of water (Murphy and Nichols 1913; Nichols 1920; Hatch et al. 2013), landing on ships at sea (Haagner 1921; Thomas 1921; Norton

1930; Griffin 1940; Carter 1950; Brown 1953; Mackiewicz and Backus 1956; Van Deusen 1961; Peterson 1970; Esbérard and Moreira 2006), roosting on gas and oil platforms (Boshamer and Bekker 2008), arriving on remote islands (Allen 1923; Hitchcock 1943; Van Gelder and Wingate 1961; Tenaza 1966; Cryan and Brown 2007; Petersen et al. 2014; Paracuellos et al. 2020), or otherwise encountered in areas or situations suggesting the animals travelled over large bodies of water (Merriam 1887; Miller 1897; Saunders 1930; Maunder 1988). Acoustic, radar, and high-altitude videography surveys in the Gulf of Maine (Peterson et al. 2014, 2016) and in the Mid-Atlantic (Geo-Marine 2010; Hatch et al. 2013; Sjollema et al. 2014; Peterson et al. 2016; Craven et al. 2020) have revealed some offshore bat activity patterns and behavior in North America. Despite these efforts, the frequency and extent of seasonal bat foraging and migration activities in the North American marine environment is poorly understood, and the degree to which bat populations can potentially be impacted by offshore wind development is largely unknown.

Methods

We aim to elucidate which North American bat species are most at risk, when and where we might expect the highest fatalities assuming the risk to bats by offshore is similar to terrestrial wind energy development, and whether aspects of offshore bat behavior can help inform mitigation strategies for reducing impacts by offshore wind energy development. We synthesize information from historic oceanic records and more contemporary records to gain a better understanding of the offshore occurrence and behavior of North American bats, and to place this in the context of offshore wind energy development in the United States. We exclude data on bat use of the Great Lakes (e.g., McGuire et al. 2012) from our review, although some of the patterns and behaviors described here may be applicable to bat use of inland lakes.

We restrict our review to sightings of bats at sea, and to acoustic recordings collected at offshore structures devoid of vegetation (e.g., buoys), to best characterize bat migratory behavior over the open ocean. Coastal data (e.g., Moore 2015; Moore and Best 2018) and records from islands containing vegetation (e.g., Johnson and Gates 2008; Johnson et al. 2011; Peterson et al. 2014, 2016; Dowling et al. 2017; Dowling 2018; Dowling and O'Dell 2018) were not included in our review because these features likely harbor resident populations of bats and/or contain habitat attractive for roosting and foraging bats. Use of the marine environment by bats has been studied more extensively in European waters, including surveys at operating offshore wind farms, and we incorporate information from these studies to provide framework for the behavior of North American species.

Several biases are inherent to this review. Sightings of bats flying over the ocean are necessarily restricted to daytime hours and to an observer's viewshed, so most sightings are reported during daylight hours and within a few dozen meters. As well, most sightings reported here were opportunistic, made while observers were engaged in other activities. Acoustic surveys can capture nighttime bat activity and are typically more rigorous and systematic than sightings from boats, but recordings are limited to the range of the detector—approximately 30 m for most species (Adams et al. 2012)—and require that bats actively echolocate while flying over the water. There is evidence that some European species echolocate over water (Ahlén et al. 2009), but hoary bats in North America are capable of making inconspicuous echolocation calls or flying without echolocating at all (Corcoran and Weller 2018). Population impacts due to collision with offshore turbines are also impossible to assess because the population size of species likely to collide with offshore turbines is unknown, as is the proportion of those populations that flies over the ocean, or that might encounter turbine blades. Despite these limitations to the data, we think a thorough examination of North American oceanic records is needed as a starting point for understanding potential risks to bats in the offshore environment and identifying knowledge gaps moving forward.

Spatial Distribution

All records of North American bats flying over the open ocean have occurred in the Atlantic region between North Carolina and Nova Scotia (Tables 1, 2; Figure 1). To our knowledge, North American bats have never been observed or acoustically detected flying over the Pacific Ocean, though hoary bats are believed to migrate south along the Pacific Coast in autumn (Brown 1935; Dalquest 1943). Several species are known to occupy Pacific islands (San Juan Islands, Dalquest 1940; Vancouver Island, Dalquest 1943; Haida Gwaii, Burles et al. 2014; Channel Islands, Brown and Rainey 2018). Hoary bats and western red bats (*Lasiurus blossevillii*) have used Southeast Farallon Island, located approximately 32 kilometers (km) off the northern California coast, as a migratory stopover for the past four decades (Tenaza 1966; Cryan and Brown 2007). Genetic evidence recently identified a juvenile eastern red bat on Santa Cruz island, 32 km off the southern California coast (Brown and Rainey, in prep). Combined with genetic confirmation of four specimens in southern California museums (Z. Haidar and D. Fraser, unpublished data), this extends the known distribution of eastern red bats by approximately 800 - 1200 km (Geluso and Valdez 2019; Solick et al. 2020a). Hoary bats are the only extant bat species to colonize the Hawaiian Islands, where reproductive isolation and morphological differentiation after multiple dispersal events led to the formation of a new species, the Hawaiian hoary bat, *Lasiurus semotus* (Russell et al. 2015; Pinzari et al. 2020). The rest of our review focuses on records from the Atlantic region of North America.

When specified, bats were visually observed flying over open water or landing at ships at sea between 2.6 and 817.3 km from the nearest land (n = 37 records; median = 39.2 km; Table 1; Figure 1). Acoustic surveys in the Mid-Atlantic and Gulf of Maine recorded bats at various offshore structures (e.g., buoys, lighthouses) between 5.9 and 41.6 km from land (Table 2; Figure 1; Peterson et al. 2014, 2016). Ultrasonic detectors mounted on research and fishing vessels that traveled within 166 km of the Mid-Atlantic coast recorded bats an average of 8.7 km (n = 166 passes; range = 1.2 – 21.9 km; Sjollema et al. 2014), 29.6 km (n = 584 passes; range 22.2 – 44.4 km; Craven et al. 2020), and 60.3 km (n = 35 passes; range = 1.2 – 129.6 km; Peterson et al. 2016; Table 3) from land. A thermal imaging camera (paired with a vertically pointed radar and mounted to a barge) monitored for birds at temporary locations within 0 – 20 km of the New Jersey coast and detected 45 signatures characterized as foraging bats (Geo-Marine 2010; Table 3). Nearly two-thirds (62.5%) of records occurred over water shallow enough to be effectively developed with current technology (i.e., < 60 meters [m] deep; Tables 1, 2; Figure 1). Six records occurred over water currently leased for wind development, and six more were in the vicinity of the newly constructed Coastal Virginia Offshore Wind Project (Figure 1). In summary, bats have been seen and detected over a wide area of the Mid-Atlantic and Gulf of Maine, occurring in areas currently developed for wind and projected for future offshore wind energy development (Musail et al. 2016).

Activity Rates

Most sightings occurred during daylight hours, and all 38 sightings occurred over a span of 130 years (Table 1), which could imply that offshore bat occurrence is relatively rare. However, multi-year acoustic surveys in the Mid-Atlantic and Gulf of Maine indicate the nocturnal density of offshore bats and the frequency at which the animals pass by fixed locations at sea is more common, averaging 2.57 passes/night at offshore structures (n = 32 site-years; Table 2; Figure 1; Peterson et al. 2014, 2016). Activity rates of bats recorded at wind turbines and research platforms in the North Sea of Europe averaged 1.01 passes/night (n = 7 sites; Table 4). Both sets of activity rates are relatively low, and are comparable to rates typically recorded in open, arid regions of the United States (Weller and Baldwin 2012; Solick et al. 2020b), suggesting that bat migration over the ocean is generally dispersed over a relatively wide, featureless area.

The standard deviation (3.51 passes/night) and the range (0 – 14.49 passes/night; Table 2) for North American bat acoustic activity data are quite broad, reflecting relatively high interannual variation in activity rates within and between sites. For example, during five years of acoustic monitoring at Matinicus Rock, located 32.9 km off the Maine coast, annual activity rates ranged between 0.41 and 12.06 passes/night, and the maximum number of passes recorded within a single night each year ranged between 21 and 326 passes/night (Table 2). Acoustic data provide an index of bat activity, not abundance (Barclay 1999), so the 326 passes at Matinicus Rock may indicate foraging or exploratory behavior by one bat or by a relatively small number of bats passing by the microphone multiple times, not 326 commuting individuals. Regardless, the relatively high degree of variation indicates bat use of structures in the offshore environment is uneven between years, and suggests prevailing weather patterns (Cryan and Brown 2007) or some other stochastic factor likely determine when and how bats encounter offshore structures during migration.

Temporal Variation

All of the Atlantic bat sightings occurred during the autumn: eight in August (including the late July-early August *Myotis* record), 25 in September (11 of which were videographed during aerial surveys on a single morning; Hatch et al. 2013), and four in October (Table 1). On Bermuda, located 1000 km offshore and where long-distance migrating bats have presumably been blown off-course by weather, "a minimum of 100 bats is likely to occur during the fall migration (in a normal year) and perhaps half that number during the spring migration" (Van Gelder and Wingate 1961: 6). Likewise, on Southeast Farallon Island in the Pacific, hoary bats were seen during the autumn months for 36 of 38 years that records were kept (mean ± standard deviation [sd] = 8.2 ± 6.6 bats; median = 6) compared to just two years that bats were seen during the spring (Tenaza 1966; Cryan and Brown 2007). Acoustic records in the Gulf of Maine (including offshore structures, coastal areas, and islands) support this seasonal timing of offshore bat activity, with >99% of 75,058 recordings made between 15 July and 15 October, despite just 56% of sampling occurring during this period (Peterson et al. 2014). Bat activity peaked in August at offshore structures in the Gulf of Maine and Mid-Atlantic (mean ± sd = 8.0 ± 1.2; range = May – October; Table 2). The timing of bats in the offshore environment coincides with autumn migration, and with the period of highest bat fatalities at land-based wind facilities in North America (Arnett et al. 2008; AWWI 2020). The general lack of oceanic records during other seasons suggests bats primarily make use of the offshore environment during autumn migration, and that risk of fatality at offshore wind facilities is lower during the rest of the year.

Activity rates for bats recorded during acoustic surveys at offshore structures in the Gulf of Maine and Mid-Atlantic peaked a few hours after sunset (mean ± sd = 2.5 ± 1.7 hours after sunset), with a range in peak activity between one and seven hours after sunset (n = 28 site-years; Table 2). However, detectors at three offshore structures recorded bats during daylight hours (n = 130 passes; Peterson et al. 2016), and sightings of bats in the Atlantic mainly occurred during the day (91.7% of 24 records that recorded time), with several bats seen as late as 11:00 – 12:00 in the morning and one bat seen an hour before dusk (Table 1). Therefore, while most bats fly over the ocean at night, some bats will be active during daylight hours, likely in search of a place to land.

Species Composition

At least six species of bat have been documented off the Gulf of Maine and Mid-Atlantic coast (Tables 1, 2; Figure 2). The vast majority of visual and acoustic records identified to species were of eastern red bats. Silver-haired bats and hoary bats made up most of the remaining observations, while tri-colored bats, big brown bats, and *Myotis* bats were relatively rare. The species composition likely reflects both differences among species in relative abundance and factors that make some species easier or harder to detect.

A review of museum specimens indicates eastern red bats occur throughout coastal areas along the Atlantic Ocean and Gulf of Mexico, extend inland in the spring, and then migrate south along the Atlantic coast in the fall (Cryan 2003). Automated telemetry of a nanotagged eastern red bat along the coast indicates individuals of this species can travel at least 453 km over water in a single night (Dowling et al. 2017). Eastern red bats were reported during 68% of 38 sightings (Table 1), and were the most frequently recorded species (89% of 3,489 passes classified to species) at 88% of offshore structures during acoustic surveys in the Mid-Atlantic and Gulf of Maine (Peterson et al. 2016; Figure 2). Eastern red bats were the main species recorded at 75% of sites (Figure 2), including at NERACOOS Buoy E, located 18.8 km off the shore of Maine. Remarkably, bats were recorded at this buoy for over 70% of nights in August of 2012, when approximately eight passes/night were recorded on average for nine consecutive nights (Peterson et al. 2016). These data suggest either a pulse of migration past this buoy—possibly evidence of flocking behavior—or that bats were using this buoy as a temporary roost.

Silver-haired bats were the next most commonly seen species offshore, accounting for 15% of sightings, including one instance when red and silver-haired bats were observed flying together as part of a large mixed flock (Thomas 1921; Table 1). Acoustic detections of silver-haired bats were less frequent than for red bats (5%; Figure 2). Some silver-haired bats apparently do not migrate, with individuals found hibernating in Minnesota and Michigan (Beer 1956; Kurta et al. 2017), and others overwintering in moderate Pacific Northwest climates (Izor 1979; Nagorsen et al. 1993). Specimens for silver-haired bats have been collected during the autumn on the Atlantic coast, indicating coastal migration in the east (Cryan 2003). Silver-haired bats were detected at 63% of offshore structures, though were more frequently recorded at sites located closer to land (Figure 2), suggesting that this species migrates relatively close to shore, at least at relatively low altitudes.

Hoary bats have not been seen flying over the ocean (Table 2). Museum records and stable isotope analysis suggest hoary bats migrate from the interior of the country to the coasts in search of more moderate climates, and potentially do not actually engage in pronounced latitudinal migration (Cryan 2003; Cryan et al. 2014b). Indeed, there is some evidence that at least some hoary bats can potentially hibernate for all or part of the winter in habitats with stable, nonfreezing climates (Weller et al. 2016; Marín et al. 2020). Three male hoary bats captured in northern California and tracked over the fall and winter using miniature GPS tags and data loggers exhibited a variety of movement patterns, but none of the bats were recorded flying over the Pacific Ocean (Weller et al. 2016).

Despite the general lack of visual records, acoustic surveys indicate hoary bats were widespread in the Atlantic Ocean, present at 88% of offshore structures, though hoary bats were infrequently recorded (4% of passes; Figure 2). Hoary bats are strong, long-distance fliers, and produce a distinct echolocation call, so it is surprising that members of this species are not more frequently observed or acoustically detected over the Atlantic Ocean. Hoary bats have routinely been observed during the autumn on Bermuda (Allen 1923; Van Gelder and Wingate 1961), and have been collected as far away as Iceland (Hayman 1959), the Orkney Islands (Barrett-Hamilton 1910), Southampton Island (Hitchcock 1943), and Newfoundland (Maunder 1988), so it is likely that some hoary bats do migrate over the Atlantic, though perhaps not to the same extent as eastern red and silver-haired bats. Hoary bats have been documented flying at 2,400 m during autumn (Peurach 2003), and can forego echolocation or produce undetectable echolocation “micro calls” in flight (Corcoran and Weller 2018), so it is possible that hoary bats (and other species) are more common offshore but potentially fly too high and too quietly to be seen or detected.

As with land-based wind development, it appears that long-distance migrating bats are the species most at risk from offshore development. However, species that do not migrate long-distances, such as tri-colored bat (*Perimyotis subflavus*; but see Fraser et al. 2012) and big brown bat (*Eptesicus fuscus*), have been detected acoustically up to 12 – 14 km from shore at locations in the Gulf of Maine (Figure 2; Peterson et al. 2016). Remarkably, *Myotis* bats are the most widespread species detected acoustically in the Gulf of Maine, being detected on all eight offshore structures for which species data were provided, and *Myotis* were the only species detected (n = 2 passes) at the most distant structure, NERACOOS Buoy I, located 26.2 km from land (Figure 2). Echolocation calls by *Myotis* can be confused with steep calls made by eastern red bats (Britzke et al. 2013), so it is possible some of these calls were misclassified. *Myotis* species were more active at structures closer to shore, with 83.3% recorded at structures 8.3 km or less from shore (Figure 2). Sjollema et al. (2014) recorded *Myotis* species up to 11.5 km from shore on research and fishing vessels in the Mid-Atlantic. Nanotag telemetry of a little brown bat (*Myotis lucifugus*) captured on the island of Martha's Vineyard, Massachusetts, found that the bat traveled at least 78 km to a mainland location on Cape Cod, which required some overwater travel (Dowling et al. 2017). One ship record indicates that *Myotis* species are capable of traveling much further from shore. Thompson et al. (2015) describe dozens of unknown *Myotis* bats (probably *M. lucifugus*) landing and roosting on their ship as well as on tall "high flier" buoys in the region, 110 km from the nearest land (Table 1; Figure 1). This event occurred in late July or early August, and the bats were believed to have been feeding on relatively large numbers of biting flies present at the time. In the Baltic Sea, approximately 36% of observations at sea (n = 1,062) were of non-migratory species feeding on flying insects and apparently gleaning amphipods from the water surface (Ahlén et al. 2009).

Group Size

Bats were seen flying alone for 79% of records (Table 1), suggesting that offshore migration is largely a solitary activity. Several records reported large groups of bats flying together in the "dozens", or estimated at 100-200 individuals (Table 1). All of the records for large groups of long-distance migrating species were from 1949 or earlier. Mearns (1898) reported "great flights" of eastern red bats over land during autumn in the Hudson Valley of New York. Loose aggregations of eastern red bats during autumn have also been reported migrating over land in Washington, D.C. (Howell 1908), while concentrations of this species in southern states were noted by Baker and Ward (1967), LaVal and LaVal (1979), and Saugey et al. (1989). It is unknown whether this flocking behavior no longer occurs due to apparent population declines (Winhold et al. 2008), or whether eastern red bats continue to gather and flock in the autumn, unobserved at night. The 11 eastern red bats reported over a three-hour period on a single morning by Hatch et al. (2013; Table 1), though flying singly, seem reminiscent of Howell's observation from a century earlier. However, all of these reports of apparent groups size for bats were made during the daytime, which may not be representative of typical nighttime migration behavior.

Sex and Age

Only 11 oceanic records noted the sex of captured or collected individuals: six bats were male and five were female (Table 1). Age was not specified. Presumably, bats susceptible to collision with offshore installations would comprise adult and juvenile bats of both sexes, as they do on land.

Flight Height

None of the records from ships state the precise height at which bats were seen flying, though Murphy and Nichols (1913: 7) describe bats flying "about a gun-shot" above the sea, Griffin (1940) notes a bat "flew within 15 or 20 feet" (4.5 – 6.0 m) and A. Rabon and J.B. Thornton (pers. comm) photographed an unknown *Lasiurus* circling their boat at approximately 9 m (Table 1). Bats migrating over the Baltic Sea were most often seen flying less than 10 m above the water surface (Ahlén et al. 2009), including the common noctule bat (*Nyctalus noctula*), which is normally a high-flying species over land (Ahlén et al. 2007). Nathusius' pipistrelles (*Pipistrellus nathusii*) were seen flying at heights between 3 – 20 m during ship-based surveys on the North Sea (Boshamer and Bekker 2008; Lagerveld et al. 2014). Bats flying low over water have reduced flight costs ("aerodynamic ground effect"; Johansson et al. 2018), and can potentially also use echolocation to remain oriented with the water surface (Ahlén et al. 2009). North American bats flying over the ocean in a similar manner would be less likely to encounter turbine blades. However, bats have been observed ascending rapidly when encountering vertical structures, such as ships, lighthouses, or wind turbines (Ahlén et al. 2009). Off the Atlantic coast of the United States, eastern red bats have been estimated flying 100 – 200 m and > 200 m over the ocean based on parallax measurement of aerial video (Hatch et al. 2013; Table 1). Five of the six bats estimated at these heights were videographed in the vicinity of the recently built Coastal

Virginia Offshore Wind Project, whose turbine blades reach 222 m above sea level (Table 1; Figure 1). Long-distance migrating bats in general are capable of flying at altitudes up to at least 460 m (silver-haired bat) to 2,400 m (hoary bat) as evidenced by collisions with aircraft (Peurach 2003; Peurach et al. 2009; Biondi et al. 2013). Bats have been recorded flying at nacelle height (93 m) at an offshore wind farm in the North Sea, albeit at a much lower rate (0.02 bats/night) than bats recorded at the base of turbines (16 m; 0.18 bats/night; Brabant et al. 2019; Table 4). These detectors could only record bats emitting echolocation pulses > 30 kilohertz (kHz; Brabant et al. 2019), which likely reduced the overall bat activity recorded.

Weather

Only 22 (60% of 37) oceanic accounts describe the weather conditions when bats were sighted (Table 1). Three records describe light winds out of the northwest or west-northwest, while a fourth record mentions an east wind. Four of the accounts took place during periods of relatively calm weather, and the authors suggest that the bats were likely not driven offshore by severe weather. In contrast, the large flock of approximately 200 eastern red bats reported by Carter (1950: 350) was seen on a day with “rain and west-northwest winds of 20 miles per hour” (32.2 kilometers per hour). As well, the eastern red bat reported 804.7 km from Nova Scotia by Brown (1953: 139) was “believed by the ship’s crew (to) have been driven out to sea by strong winds”, although the actual weather conditions were not described. Sjollema et al. (2014) and Craven et al. (2020) found that bat activity off the mid-Atlantic coast decreased with increasing wind speeds, a relationship that has also been found in the Baltic Sea (Ahlén et al. 2007), on Assateague Island (Johnson et al. 2011), and at multiple land-based wind energy studies (Reynolds 2006; Arnett et al. 2008; Horn et al. 2008; Weller and Baldwin 2012; Baerwald and

Barclay 2011). That said, Hatch et al. (2013) reported bats flying with tailwinds between 8.9 and 10.1 m/s (n = 12 records; Table 1), indicating that bats are capable of flying at relatively high wind speeds offshore.

Offshore Wind Development

It is unknown what impact, if any, that offshore wind development might have on bat populations or whether any mitigation is needed. In the absence of empirical data, the similar species composition and patterns of bat activity in onshore and offshore environments suggests that bats flying offshore are at some risk of collision. To date, no fatalities of bats have been documented at offshore wind energy facilities worldwide. However, searching for carcasses beneath offshore turbines is not possible, and monitoring of offshore turbines using camera technologies (e.g. thermal, near infrared) that could witness collisions is at very early stages of development and has only been recently pilot-tested (Brown-Saracino 2018; Good and Schmitt 2020; Matzner et al. 2020; Normandeau Associates 2021). It is unknown what the potential population impacts could be to bats from offshore wind development. The population size for long-distance migrating bat species is poorly understood, and it is unclear what proportion of bats move over water as opposed to land. Taken alone, the relatively low numbers of oceanic records in the literature (Table 1) could imply offshore migration is generally a rare event. Yet the acoustic recordings described in this review (Tables 2, 3) indicate regular, albeit unconcentrated, movement of bats over open water, at least in the Gulf of Maine and the Mid-Atlantic. What is known is that the vast majority of offshore bat records are of long-distance migrating bats and occur during autumn migration, the period when the highest fatality rates of these same species at land-based wind turbines in North America have been recorded (AWWI 2020). It is prudent to assume that bats flying offshore are at similar risk of collision with turbine blades as conspecifics flying over land. Then again, if offshore wind speeds are typically greater than wind speeds on land, it is possible that bats flying over the ocean area at less risk of collision.

Offshore turbines could be more attractive to bats than mainland turbines. Solick et al. (2020b) found that bat activity rates increased in a location after turbines are built, and Cryan and Brown (2007) and Baerwald (2018) hypothesized that bats could be attracted to prominent landmarks such as turbines in an otherwise featureless landscape. Some wavelengths of light are attractive to some European migratory species (Voigt et al. 2017, 2018), and the contrast of bright lights against a dark ocean could potentially amplify this attraction. Exploratory behavior by bats to investigate potential landing spots, evaluate feeding opportunities (e.g., Hüppop and Hill 2016, Brabant et al. 2019), or inspect novel structures on the landscape could increase the probability of collision with moving turbine blades. Prior to landing on ships, bats were observed circling vessels on three occasions (Table 1), presumably inspecting the vessel before landing or moving on. Thermal video at a wind farm in Indiana captured 993 bat detections, of which 88% exhibited "focal" exploratory behaviors, including close approaches to the tower, nacelle, or blades, and the bats often approached multiple times over a period of several minutes (Cryan et al. 2014a).

Offshore structures can provide shelter from adverse weather or an opportunity to rest after a long flight. Indeed, for 12 of the 19 records by ship (63.2%), observers describe bats landing on the rigging, on other parts of the ship, and even on people (Table 1), presumably from exhaustion. On two occasions, bats remained aboard until the ship returned to harbor (Table 1). In the North Sea, bats have been found roosting on offshore installations (Boshamer and Bekker 2008; Petersen et al. 2014; Hüppop and Hill 2016), and the animals are likely using structures as temporary refugia during migration. In both the Baltic and North Seas, bats have been found roosting in the nacelles of turbines (Ahlén et al. 2007, 2009), as well as in a transformer station (Lagerveld et al. 2016), inside turbine foundations (Brabant et al. 2019), and in the maintenance equipment on a turbine service platform (Brabant et al. 2019).

Offshore structures can potentially also provide feeding opportunities for migrating bats. Nathusius' pipistrelle exhibits a "fly-and-forage" strategy during autumn migration along the coast of Latvia (Šuba et al. 2012), and North American long-distance migrating bats feed during autumn migration as well (Reimer et al. 2010; Valdez and Cryan 2013), including in the vicinity of wind facilities (Foo et al. 2017; Reimer et al. 2018). Migratory and non-migratory bats were regularly observed foraging on high densities of insects at wind farms located 9.1 – 14.2 km off the coast of Sweden. Chironomids of marine origin were common offshore, as were terrestrial insects that had flown or drifted from neighboring countries, including ballooning spiders (Ahlén et al. 2007, 2009). So-called "bioflows" of "aerial plankton" containing trillions of insects amounting to thousands of metric tons of biomass (Hu et al. 2016; Satterfield et al. 2020) can sometimes occur over the open ocean (Alves et al. 2018), and can potentially provide strong incentive for insectivorous bats to seek out and/or follow. The occurrence of "dozens" of *Myotis* bats—not typically associated with long-distance flight—110 km offshore for a 24 hour period

(Table 1), ostensibly feeding on large numbers of biting flies, may be an example of North American bats exploiting a bioflow.

Bats have been observed foraging in close proximity to turbine blades over land and over water (Horn et al. 2008; Ahlén et al. 2009). "Hill-topping" is a behavior whereby insects follow a hill (or other tall structure) upwards and congregate at the top (Shields 1967). Applied to turbines, this could place foraging bats within proximity of spinning blades (Rydell et al. 2010). Lidar mounted on the nacelles of land-based turbines and paired with bat detectors documented nightly insect swarms and bat feeding activity (Jansson et al. 2020). Insects are most abundant during nights with low wind speeds, and bats are also most active on nights with low wind speeds (Baerwald and Barlcay 2011). Thus, as with land-based facilities, the greatest risks to bats at offshore wind facilities are to long-distance migrating bats on low wind speed nights.

Foraging bats may also be attracted by marine organisms in the open ocean. Ahlén et al. (2009) observed two species of bats regularly dipping into the water with their feet and hypothesized the bats were gleaning the numerous and widespread amphipods. In the Gulf of California, the fish-eating bat (*Myotis vivesi*) feeds on fish and crustaceans captured in the ocean (Otálora-Ardila et al. 2013). In the San Juan Islands, Washington, Yuma bats (*M. yumanensis*) and California bats (*M. californicus*) were shot while flying low and dipping into salt water off the coast (Dalquest 1940). It is possible these bats were also foraging on marine organisms.

Given bat use of offshore structures—including turbines—as temporary roosts, and the potential abundance and availability of insects at wind farms, it is possible that offshore creation of roosting and foraging habitat could benefit bat populations. However, is roosting and foraging in the vicinity of turbine blades could increase exposure and risk of collision with turbine blades (Peterson 2020). Alternately, creation of roosting and foraging habitat at offshore structures could potentially benefit bat populations and help offset losses from turbine collisions. Until Turbines located offshore may pose additional risks to bats compared to mainland counterparts. Bat fatalities increase with turbine height (Barclay et al. 2009), and offshore turbines are taller than land-based turbines (Musail et al. 2016). As noted earlier, bats fly during daylight hours over the ocean and, if this behavior is more common than on land, they may be at greater risk of colliding with offshore turbines throughout the 24-hour period. Lastly, bats have collided with lighthouses, buildings, and television towers during periods of fog or low ceiling height (Saunders 1930; Van Gelder 1956; Cryan and Brown 2007). These weather factors are more common at sea and can potentially increase the risk of collision for bats with offshore turbines.

At present, it is not possible to estimate fatality rates for bats at offshore facilities, and technologies to monitor activity and assess risk are limited. Radar has been used to monitor bat movements over the Baltic Sea, but could only track the large-bodied common noctule bat (average mass = 30 grams [g]; Ahlén et al. 2007). The thermal imaging camera and vertically pointing radar used off the coast of New Jersey only documented 45 bats during approximately 520 hours of surveys due to the limited field of view and inability to reliably distinguish commuting bats from birds (Geo-Marine 2010). Impact sensors within rotor blades can reliably detect collisions with 57 g tennis balls fired from an air cannon (Hu et al. 2018), but it is unknown if these sensors can detect collisions of long-distance migrating bats weighing 8 – 40 g. Acoustic detectors mounted on offshore structures provide information on species composition, timing, and relative activity rates for bats. We recommend that more offshore acoustic monitoring take place to better understand offshore bat activity patterns, particularly on operational turbines, during the 24 h period, and in the Pacific Ocean, but these acoustic monitoring devices are limited by detection range. As well, a recent meta-analysis of land-based wind facilities in North America concluded that bat activity rates do not predict fatality rates (Solick et al. 2020b), so offshore activity rates may not be a good indicator of risk. Lagerveld et al. (2020) evaluated three systems combining radar, thermal cameras, and acoustic detectors to monitor for bats flying near turbine blades, but conclude none of the systems are currently ready for deployment in the offshore environment. However, two Acoustic and Thermographic Offshore Monitoring (ATOM^{TM}) systems were recently deployed at the Coastal Virginia Offshore Wind facility as part of a pilot project (Normandeau Associates 2021).

Acoustic deterrents generating high frequency noise audible to bats have been found to reduce overall bat fatalities at land-based wind facilities in North America by up to 62% (Romano et al. 2019; Schirmacher 2020; Weaver et al. 2020). However, this reduction of bat fatalities varies widely by technology and region, and between years, and between species. For example, during three years of study at a facility in Illinois, a General Electric deterrent reduced bat fatalities by approximately 30% in 2014 and 2015, but no reduction was observed in 2016 (Romano et al. 2019). In Texas, an NRG Systems deterrent reduced fatality rates of hoary bats and Mexican free-tailed bats (*Tadarida brasiliensis*) by 78% and 54%, respectively, but had no effect on fatalities for northern yellow bats (*L. intermedius*; Weaver et al. 2020), a species frequently found at wind facilities in the southwestern U.S. (8.1% of fatalities; AWWI 2020). Eastern red bats appear to be the main species at risk of collision with offshore turbines in the Atlantic, but none of the deterrent systems reliably reduced fatality of this species when it was present at a facility. As such, acoustic deterrents by themselves do not appear to be a currently viable mitigation strategy at offshore wind facilities.

Adjustments to turbine operations can potentially be the most effective mitigation strategy for reducing impacts to bats offshore. Land-based wind facilities in North America have tested raising the turbine cut-in speed (i.e., the wind speed at which wind-generated electricity enters the power grid) from the manufactured speed (usually 3.0 – 4.0 m/s) by 1.5 – 3.0 m/s, and found at least a 50% reduction in bat fatalities (Arnett et al. 2013). Economic analyses of land-based facilities in North America suggest this type of operational mitigation is likely to result in < 2 – 5% energy production loss (Baerwald et al. 2009; Arnett et al. 2011; Arnett et al. 2013; Martin 2015; Dowling 2018). Modeling of theoretical offshore wind facilities in the Atlantic indicates that standard operational mitigation for bats would result in ≤ 1.12% decrease in energy production, and ≤ 0.88% revenue losses based on local marginal price data (Dowling 2018). Wind speeds are generally greater offshore, so low wind speeds (e.g, < 6.0 m/s) associated with curtailment would contribute a lower proportion of annual energy production for offshore wind facilities (Eurek et al. 2017; Dowling 2018). Detection-based "smart curtailment", which employs operational mitigation only when bats are detected during high-risk periods (e.g., wind speeds < 6 m/s during August and September), combined with predictive models of offshore bat activity based on regional weather patterns (Smith and McWilliams 2016), can potentially reduce energy production and revenue losses even further (Hayes et al. 2019). However, because winds tend to be stronger offshore and bats fly at higher wind speeds over the ocean (Hatch et al. 2013; Sjollema et al. 2014; Table 1), operational cut-in speeds for offshore turbines potentially also need to be increased (and possibly applied during daytime hours) to effectively reduce impacts to bats. A combination of smart curtailment with other mitigation strategies, such as acoustic deterrents or making turbines more visible to bats with ultraviolet light (Gorresen et al. 2015), can potentially be the most effective means for harnessing offshore wind energy generation while minimizing potential impacts to bats.

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ACKNOWLEDGEMENTS We are grateful to P. Brown, D. Fraser, Z. Haidar, D. O'Dell, C. McKeon, K. Sutherland, and J. Thornton for contributing their records to this review and helping us network to locate other records. We thank J. Cicarelli for producing our map and assisting with tables, C. Nations for producing Figure 2, A. Palochak for providing many references and exemplary technical editing, and P. Cryan for providing obscure literary references. M. Griffiths and K. Brockheimer provided other problematic references, and M Brigham helped pinpoint the geographic coordinates for the Thompson et al. (2015) record. Lastly, many thanks to T. Peterson for laying the groundwork (waterwork?) for this review and to S. Webster for connecting the authors.

FIGURE CAPTIONS

Figure 1. Distribution of bat records and acoustic recording locations in the Atlantic Ocean, in relation to operating wind energy facilities and leased areas. BOEM = Bureau of Ocean Energy Management.

Figure 2: Species composition at offshore structures surveyed with acoustic detectors between 2009 and 2014 in the Gulf of Maine and Mid-Atlantic, adapted from Peterson et al. (2016) and arranged by distance from land.

DATA ACCESSIBILITY

Tables and figures: Dryad doi:XXXXXXXXXX. (DS has an ORCiD and Dryad account, but Dryad will not accept our data unless I supply a manuscript number or DOI).

COMPETING INTERESTS

None declared.

AUTHOR CONTRIBUTIONS

Donald Solick: conceptualization (lead), data curation (lead), investigation (lead), writing original draft (lead), writing – review and editing (equal). Christian Newman: conceptualization (supporting), funding acquisition (lead), supervision (lead), writing – review and editing (equal).