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Marine artificial light at night: Implications and potential hazards for offshore songbird and bat movements in the Greater North Sea

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Abstract

Human activity in the North Sea is intensifying, as emerging uses, such as offshore wind farms (OWFs) and liquid natural gas (LNG) terminals, are added to fishing, freight shipping, and fossil fuel production as traditional forms of resource exploitation. The volume and scale of these additional installations are projected to increase substantially in the coming decades, which amplifies the need to better understand the biological implications of human activities in the ecoregion. Previous studies have identified that offshore wind turbines either pose a physical barrier to flying animals, leading to avoidance and displacements, or act as ecological traps by interfering with sensory input, leading to increased attraction, collision risk, and mortality. Here we aim to characterize the impacts of marine artificial light pollution at night (ALAN) on offshore migratory birds and bats and discuss implications for conservation policy and practice. Considering littoral states aim to multiply the OWF capacity by a factor of eight before the year 2050, a significant increase in the cumulative impacts of ALAN can be expected. In light of these developments, we discuss the potential for scientifically informed, anticipatory, and ecosystem-based marine governance.

KEYWORDS

animal navigation, artificial light, ecosystem-based management, human pressures, marine ecosystems, migratory species, North Sea, offshore renewable energy, sensory ecology

[†]Ommo Hüppop passed away in March 2024, prior to the submission of this manuscript.

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1 | INTRODUCTION

Artificial light at night (ALAN) is an issue of global concern. A broad scientific consensus exists that ALAN has been reshaping ecosystems globally for more than 100 years (Davies & Smyth, 2018; Longcore & Rich, 2004; Marangoni et al., 2022). ALAN is known to significantly impact movement behavior across a range of taxa and spatial scales (Burt et al., 2023). While urban spaces have been the primary focus of research on artificial lighting, it is likely that increased ALAN exposure in light-naïve environments, such as marine and remote rural areas, could suffer similar or even disproportionately larger impacts than rural areas (Gaston et al., 2021). In contrast to the extensive research on ALAN effects in terrestrial ecosystems, marine habitats and species remain relatively understudied.

In the last decade, however, research efforts to assess the impacts of ALAN on ecological and biological processes in the marine environment have intensified (Marangoni et al., 2022). Sources of light pollution at sea include oil and gas platforms, shipping vessels, and light-enhanced fisheries, as well as coastal cities, ports, and harbors (Figures 1 and 2). Shipping and light-enhanced fishing vessels emit light predominantly in a horizontal plane. These light sources, therefore, are generally poorly detected via remote sensing, so their effects are understudied and most likely underestimated (Gaston et al., 2021). Effects of ALAN from shipping are likely to be significant at various scales, ranging from local attraction and disorientation of, by individual vessels to shipping lights experienced as irregular pulses confounding animal orientation and navigation cues at regional scales (e.g., Gaston et al., 2021). Lighting at sea can carry across long distances (e.g., Bruderer et al., 2018) as the direct light paths are typically only hindered by the curvature of the Earth (Loring et al., 2019). The effects of direct light emissions are further amplified by (artificial) skyglow, that is, the increase in night sky brightness due to the scatter of ALAN by atmospheric particles and molecules (Falchi et al., 2016; Figure 2). Skyglow is responsible for a reduction of star visibility which may result in a critical loss of information for animals using a star compass for orientation (Foster et al., 2018). Known and potential impacts of marine and coastal ALAN include those on navigation/orientation, reproduction and recruitment, predator–prey interactions, and communication across a wide range of species (Gaston et al., 2021).

This perspective focuses specifically on the effects of ALAN associated with increased maritime activity in the Greater North Sea on night-migrating birds (songbirds) and bats. Both taxa are land animals. The North Sea thus represents a deadly ecological barrier to be crossed when migrating between wintering and breeding sites. Seabirds, in contrast, use the sea as a habitat and foraging ground throughout the year at all life stages, that is, also, during breeding time, requiring a very different perspective on the effects and consequences of ALAN. Given these significant ecological differences, this article does not focus on seabirds. Previous studies have, however, examined the effects of ALAN on seabirds (see Marangoni et al., 2022 and Rodríguez et al., 2017, although most seabird studies deal with coastal ALAN). We have chosen to focus exclusively on songbirds and bats, whose movement behaviors are affected by ALAN on land, to address critical knowledge gaps specific to terrestrial migrants crossing offshore environments on a seasonal basis.

The North Sea constitutes a relatively confined sea space and one that has been subject to intensive pressures from human activities over hundreds of years (Emeis et al., 2015). Human use of this marine space is projected to increase significantly in the coming decades. Offshore renewable energy, carbon capture and storage, and large-scale aquaculture will add to the existing pressures on marine ecosystems associated with fishing, shipping, and mineral extraction (e.g., OSPAR, 2023; Figure 1). We can expect to see a dramatic expansion in human activities in the North Sea, as climate change mitigation policies aim for the accelerated roll-out of offshore renewable energy production. The European Commission (EC, 2020) calls for a 30-fold increase in offshore renewable energy by 2050 (to at least 300 GW). More recently, the energy ministers of northern European countries have committed to ambitious targets for the expansion of OWF to at least 300 GW by 2050, from approximately 34 GW installed capacity in 2023 (Ostend Declaration, 2023). Based on current power densities, 300 GW may be expected to cover an area of approximately 50,000 km^2 with an estimated 3000–4000 individual turbines (see also OSPAR, 2021).

EU member states were required under the Marine Strategy Framework Directive (MSFD) to achieve and maintain good environmental status for marine ecosystems by 2020. North Sea coastal states, however, have failed to achieve this status, and the North Sea continues to be in a critical state (see BMU, 2019). Conservation efforts will need to shift to ecological restoration to ensure the ecological integrity of the North Sea is not irreversibly compromised, and maritime spatial plans will need to align with EU environmental objectives (Walsh et al., 2024). At a transnational level beyond the EU, night-migratory birds crossing the North Sea are furthermore subject to international protection under the African-Eurasian Migratory Landbirds Action Plan (AEMLAP, CMS, 2014), whereas bats are protected under EUROBATS (CMS, 1991). To date, marine ALAN has received peripheral attention only within sea-basin-level assessments of the impacts of human activities on marine

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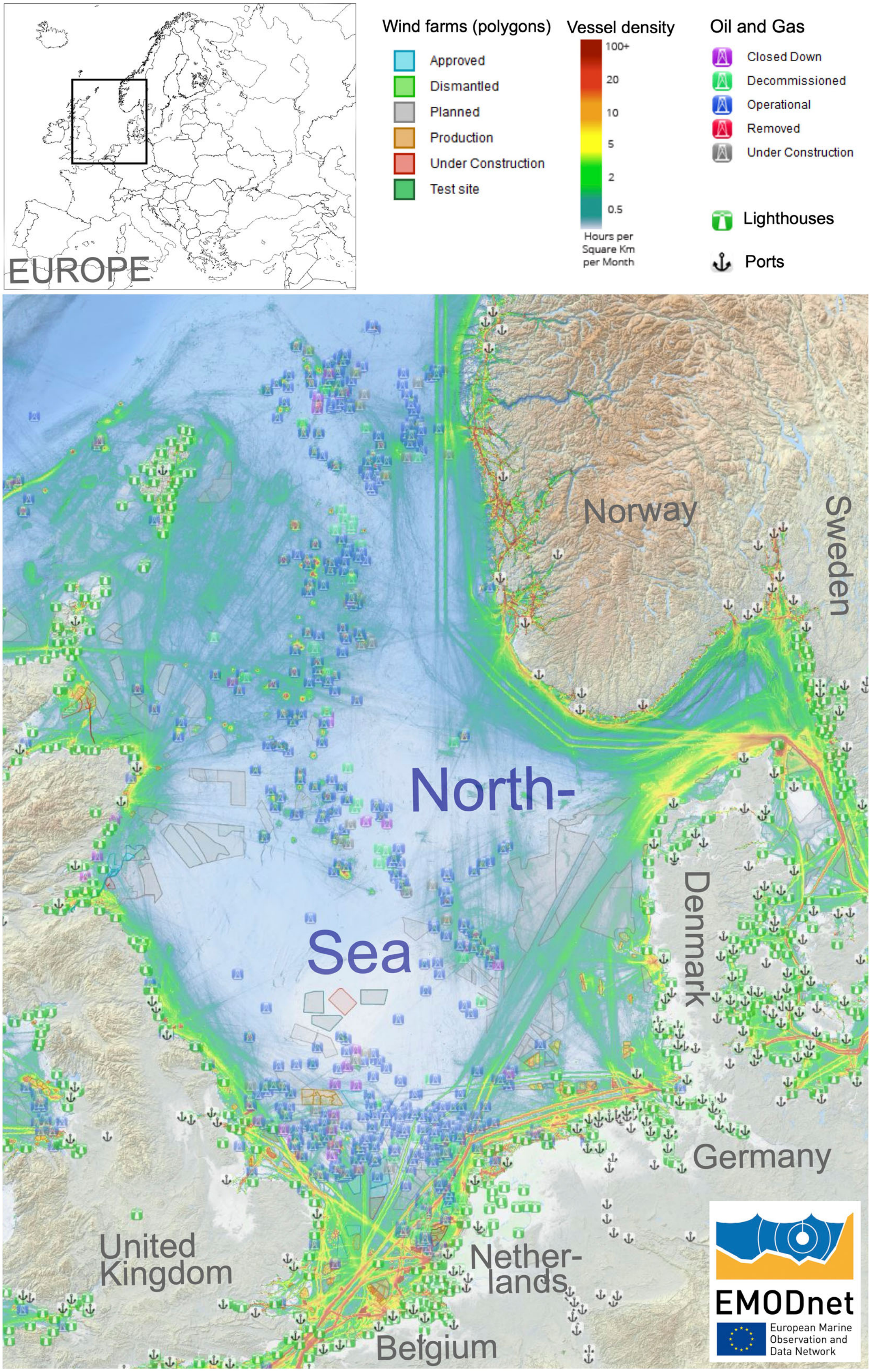

FIGURE 1 Legend on next page.

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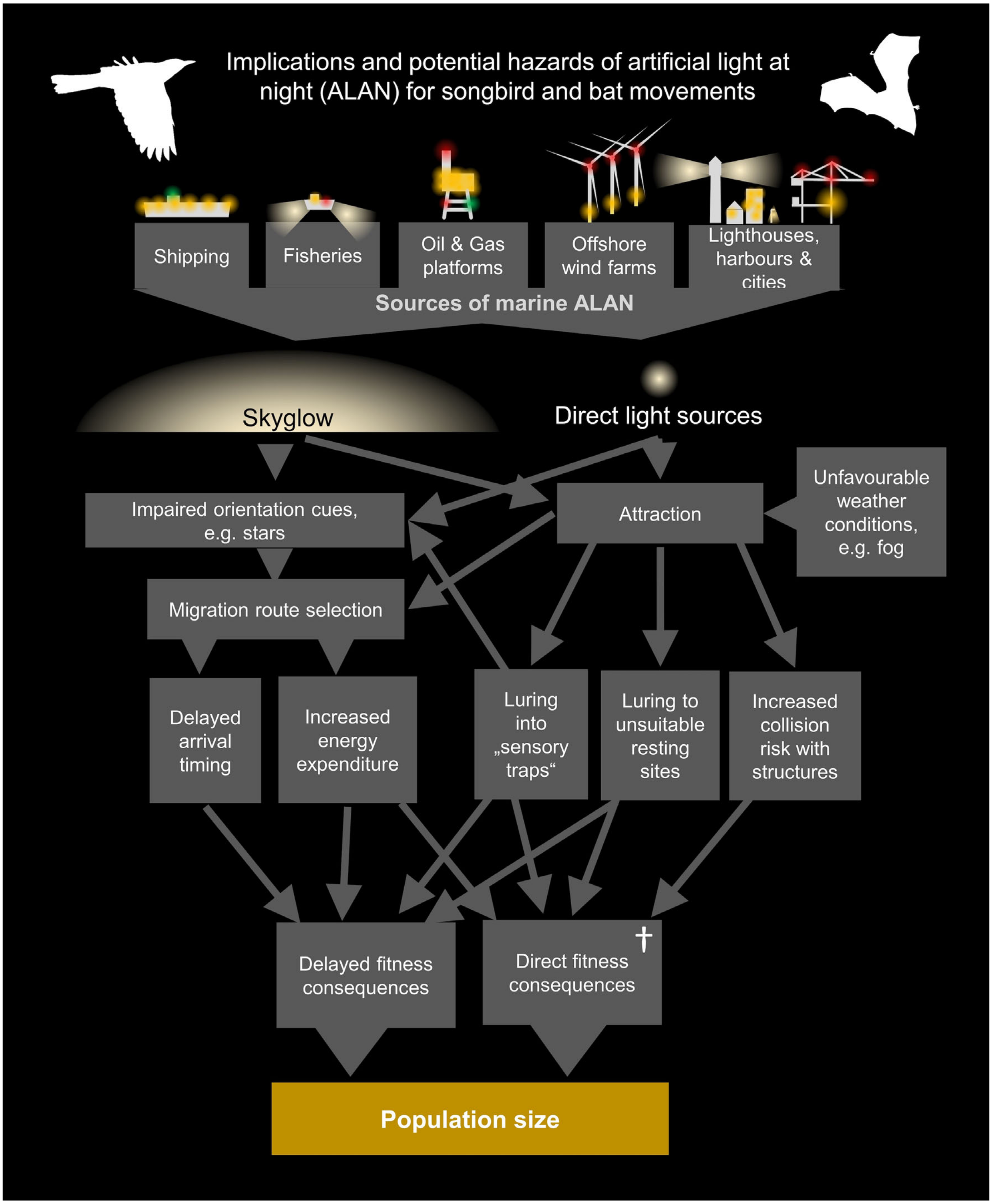

FIGURE 2 Conceptual illustration showing functional aspects and threats in the relationship between technical sea-associated infrastructure emitting light and night-migratory bat and bird behavior.

FIGURE 1 Distribution of main marine ALAN sources in the North Sea, namely, oil and gas platforms, wind farms, lighthouses, ports, and vessels. Fisheries are not displayed for reasons of comprehensibility but can be freely accessed via the same source. Source: European Marine Observation and Data Network (EMODnet), https://emodnet.ec.europa.eu/geoviewer, Accessed 19 September, 2024. Overview map contains European country borders. Source: https://de.m.wikipedia.org/wiki/Datei:Europe_blank_political_border_map.svg, Accessed 16 December, 2024. Note that other sources predict an even more extensive expansion of offshore wind, see https://map.4coffshore.com/offshorewind/. Migratory routes are not shown, as passerines and bats are broad-front migrants, meaning that they migrate dispersed across the landscape (including the sea).

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ecosystems (e.g., HELCOM, 2023; OSPAR, 2023). The 2023 OSPAR Quality Status Report recognizes the impacts of ALAN in relation to illumination on offshore oil and gas platforms but does not refer to ALAN in relation to offshore wind turbines. Within the relevant gray literature, a comparatively narrow focus on collision risk and habitat loss among birds and bats is evident (e.g., Potiek et al., 2021). The prevalence and increasing penetration of ALAN across marine and coastal areas have prompted conservation managers to seek dark sky status for protected areas (DarkSky International, 2024). Yet, given the pervasive nature of ALAN, measures specific to marine protected areas alone are insufficient. In this paper, we argue that considerations of marine ALAN are relevant for all sea spaces and must be integrated into assessments of the environmental effects of planned human activities at sea to inform decision-making at an early stage in the policy process.

2 | EFFECTS OF MARINE ALAN ON MIGRATORY BIRDS AND BATS

2.1 | Light characteristics

The spectrum of artificial light typically ranges from 350 to 800 nm (Longcore et al., 2018), which corresponds well with the wavelength of maximum absorbance of the photoreceptors of birds (Hart, 2001) and bats (Gorresen et al., 2015; Voigt et al., 2018). It remains challenging, however, to identify ALAN frequency spectra relevant to the species in focus (Longcore, 2023) because (i) most commercial light measuring equipment under-samples low-wavelength (blue to UV) frequencies, which are visible and relevant to birds and bats (also Marangoni et al., 2022), and (ii) information about spectral emissions of commercially available light sources used in the marine sector and on wind turbines is difficult to access due to proprietary restrictions and a lack of standardized reporting. Thus, either proper spectral characterization of ALAN has to be obtained from the manufacturers or specifically measured before any experimental investigation into animal response behavior (Voigt et al., 2018). Light characteristics (color, intensity, and blinking frequency) have been shown to influence the degree of attraction among nocturnally migrating birds and bats. For birds, blinking lights are less of a problem than colored lights, and red light is less impactful than light of any other wavelengths (Rebke et al., 2019; Zhao et al., 2020). For bats, in contrast, blinking lights appear to have no attraction effect (Jain et al., 2011). Migratory Nathusius' pipistrelles (*Pipistrellus nathusii*) that cross the North Sea have increased their flight activity, unrelated to foraging, around red and green lights (Voigt et al., 2017, 2018).

2.2 | Evidence for offshore migration

For night-migratory songbirds and long-distance migratory bats, water bodies such as the North Sea constitute an ecological barrier. Despite this barrier, many migratory songbirds undertake long overwater crossings (Alerstam, 1990; Bairlein et al., 2012) (for the North Sea: Brust & Hüppop, 2022; Dierschke et al., 2011; Shamoun-Baranes & van Gasteren, 2011). Rüppel et al. (2023) found that 54% of migrating songbirds from seven species crossed the southeastern North Sea instead of following a coastal route. This relative proportion of offshore vs. onshore routes is species-specific. The projected increases in offshore artificial structures will have species-specific impacts on migratory songbirds.

Due to little evidence for sea crossings in the five long-distance migratory bat species (Ahlén et al., 2009; Bach et al., 2022; Kruszynski et al., 2021), we have only started to understand the relevance of offshore routing for bats. The most plausible hypothesis for why migratory bats coming from the Baltic cross the North Sea is to reach the British Isles for hibernation (Speakman et al., 1991). Evidence about which bat populations from which littoral areas or states are crossing the North Sea regularly and where migration is concentrated is largely missing (but see Kruszynski et al. 2021).

2.3 | Known effects of ALAN on night-migrating birds

It is well known that illuminated offshore structures, such as lighthouses, light vessels, oil and gas platforms, and bright ships and research platforms, attract night-migrating birds, increasing their collision risk (e.g., Hüppop et al., 2006, 2016; Wiese et al., 2001; Figures 2 and 3), which is considered one of the key mortality threats (Loss et al., 2014). Reliable estimates of collision events with offshore structures are challenging to obtain due to several factors: the difficulty of accessing remote sea locations, the low probability of detecting collision carcasses in the water at these structures, and the technical limitations for unbiased and continuous recording of collisions and monitoring their aftereffects (Molis et al., 2019). Concentrations of migrating birds around OWFs have been detected (Hill et al., 2014), and thousands of dead birds were found in single incidents (Hüppop et al., 2016). The overall mortality for the North Sea has been estimated to be of the order of hundreds to thousands of birds per single OWF per year (Hüppop et al., 2016, see also Brabant et al., 2015). These estimates come from a 101.5 m high static lattice research tower and not from OWF with rotating rotors of the size they are currently planned (up to 300–400 m).

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(a)

(b)

FIGURE 3 Examples for marine ALAN. (a) Night view of an offshore wind farm in the North Sea during a star-clear night. Photo: T. K. (b) Migratory passerines are attracted to light on a ferry during rainy weather. The birds, redwing (*Turdus iliacus*) and blackbird (*T. merula*), have been sensory-trapped for many hours, flying back and forth between the lamps, thereby also damaging their feathers, so that the blackbird has lost all but a single tail feather. Photo: O. L.

2.4 | Known effects of ALAN on bats

Illuminated offshore structures, including illuminated wind turbines (Figure 3), pose sensory traps to bats, as these lure them in (Hüppop & Hill, 2016, Figure 2), for example, to exploit potential foraging opportunities or roost locations en route. In addition, they may forage between such structures to exploit grounded aerial insects, which themselves are concentrated at sea due to phototaxis (Ahlén et al., 2009). In contrast, bats have been observed to avoid such structures by quickly increasing flight altitude to overfly them (Ahlén et al., 2009). It is important to realize that the structures are visible to bats beyond their echolocation range (Ahlén et al., 2009; Cryan & Brown, 2007).

2.5 | Influence of weather conditions

Open-water flights are inherently risky for migrating songbirds and bats since they cannot land on the water. In adverse weather conditions such as strong winds, heavy rain, or fog, volant migrants typically seek places to land (Schmaljohann et al., 2022). However, songbird migrants occasionally select strong winds to migrate en masse over the North Sea from Scandinavia toward

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coastal Europe (Shamoun-Baranes & van Gasteren, 2011). Migrants can thus become drifted or disoriented while over water and are likely to be attracted to artificially lighted structures at sea, increasing their collision and mortality risks (Figure 3). There is a high concentration of migratory movement across the North Sea on a small number of nights, with reliable predictions of intense migration depending heavily on weather conditions (e.g., Bradaric et al., 2020; Manola et al., 2020). Adverse weather, such as overcast skies and fog, can increase attraction to artificial light (Figure 3b), as birds may struggle to use celestial cues for orientation (Hüppop et al., 2016; Rebke et al., 2019; Ronconi et al., 2015; Schmaljohann et al., 2022). Bats similarly rely on solar cues and post-sunset glow for navigation (Lindecke et al., 2019; Schneider et al., 2023). While the specific impacts of artificial light in these conditions remain unclear in birds and bats, disorientation or detours are both likely, as evidenced by individuals found near artificial light sources during migration periods (Figure 2).

2.6 | Fitness consequences

Both direct (death through collision van Doren et al., 2021) and delayed fitness consequences, such as energetically more inefficient migration or delayed arrival timing at the destination due to ALAN-disturbed longer migration routes, must be considered (Figure 2). The latter could be caused by macro avoidance behavior (Cabrera-Cruz et al., 2018; McLaren et al., 2018) or attraction to lighted ships (e.g., Boccetti, 2011) onto which migratory songbirds fall out (emergency landing, Figure 3b), which could additionally lead to misorientation and additional delays. The ultimate consequences of non-fatal ALAN effects are little understood. Secondary ALAN effects due to delays, misorientation, or compromised acquisition of resources are similarly unknown (McLaren et al., 2018). Large-scale impact assessments and population viability modeling on appropriate scales (integrating breeding success, wintering areas, and flyways) are needed to assess potential impacts on the level of (meta-)populations.

3 | IMPLICATIONS FOR POLICY AND PRACTICE

Illuminated offshore structures and mobile sources are likely to have significant adverse impacts on migratory birds and bats. Uncertainties remain regarding the extent to which impacts can be causally attributed to marine ALAN. Empirical evidence for ALAN impacts at OWFs (Figure 3a) and the extent of population-level impacts are difficult to quantify. Similarly, data on the impacts of other sources of marine ALAN, such as shipping, is comparatively limited. Nevertheless, it is plausible to assume that the planned expansion of OWFs in the Greater North Sea will, in the absence of mitigation measures, lead to higher (and potentially population-relevant) levels of collision-induced mortality and likely lead to significant indirect fitness consequences, negatively impacting the ability of night-migrating birds and bats to cross the North Sea.

An ecosystem-based approach to maritime management requires that in the absence of complete information, a precautionary approach should be adopted. Mitigation measures should be adopted to ensure that marine ALAN does not lead to adverse impacts on bird and bat populations and that the expansion of OWFs does not place the achievement and maintenance of Good Environmental Status for the North Sea at risk. The precautionary principle is relevant "in the event of a potential risk, even if this risk cannot be fully demonstrated or quantified or its effects determined because of the insufficiency or inclusive nature of the scientific data" (European Commission, 2000: 12). This implies that decisions should not be based on the best available evidence alone but should favor the conservation of marine ecosystems, where potential negative impacts may be anticipated (see also Walsh et al., 2024). Marine ALAN is, in our view, such a risk that cannot be fully quantified. Consequently, a precautionary approach is required.

Options for reducing the risks posed by OWF to night-migrating songbirds and bats include avoiding siting OWFs in areas of concentrated migration, temporary shutdowns, and the selection of the least hazardous forms of lighting (Degraer et al., 2023). Dutch authorities have introduced a shutdown protocol for selected North Sea OWFs, based on a predictive model informed by high-resolution data on bird migratory patterns and weather patterns known to be associated with peaks in bird migration movement (Bradaric, 2022). The predictive accuracy of the model is expected to improve over time as it is trained with new data (Bradaric et al., 2024). In Germany, mitigation measures are planned for the Baltic Sea coastal waters and Exclusive Economic Zone (EEZ) but are not currently planned for the North Sea EEZ. These measures are focused on controlling the illumination rather than the operation of the wind turbines (Degraer et al., 2023). Other North Sea countries have not yet implemented mitigation measures to date.

4 | CONCLUSIONS

Future research is needed to advance our understanding of the direct impacts of marine ALAN on the orientational

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and navigational performance of songbirds and bats and the precise extent of non-fatal effects over both shorter (days) and longer (years) timescales. Despite difficulties in access to offshore structures for research purposes, we find mounting evidence of significant adverse impacts of marine ecological pollution on these night-migratory animals. It is imperative that this evidence inform the planning of offshore structures and, in particular, that environmental assessments include robust analyses of the likely cumulative impacts of significantly higher densities of illuminated structures at sea. Further applied empirical studies are needed to assess the likely impacts of current and emerging sources of marine ALAN, from shipping and harbors to OWFs and LNG terminals. We recommend the further development of sensory ecology perspectives, focused on industrializing marine spaces, such as the North Sea, as ecologically sensitive areas for diverse taxa (see Martin & Banks, 2023). Finally, we encourage the further development of interdisciplinary perspectives that integrate critical analyses of processes of marine industrialization with informed assessments of current and future ecological impacts.

AUTHOR CONTRIBUTIONS

C. W. drafted Sections 1, 3, and 4 and coordinated the writing process. J. M., H. S., O. L., and T. K. drafted Section 2. T. K. prepared the figures. All authors commented on earlier drafts of the text and contributed to concept design and formulation. All authors, with the exception of OH, approved the final version of the manuscript. O. H. passed away in March 2024, prior to the submission of this manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest relevant to this publication.

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