Light Pollution at Sea: Implications and Potential Hazards of Human Activity for Offshore Bird 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 understand better 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 sensory traps attracting animals by interfering with the sensory input of natural cues, leading to increased collision risk and mortality. Here we aim to characterise impacts of artificial light pollution at night (ALAN) on offshore migratory birds and bats, and discuss implications for conservation policy and practice. Considering littoral states are aiming to multiply the OWF capacity by a factor of eight before the year 2050, a significant increase in the cumulative risk increase of ALAN can be expected. In light of these developments, we discuss the potential for scientifically informed, anticipatory and ecosystem-based marine governance.

1) Introduction

Artificial light at night (ALAN) is an issue of global concern, and a broad scientific consensus exists that ALAN has been 'reshaping nature', i.e. affecting the integrity of ecosystems for more than one hundred years (Davies et al. 2014, Davies & Smyth 2018, Marangoni et al. 2022). ALAN is known to significantly impact movement behaviour across a range of taxa and spatial scales (Burt et al. 2023). Routes of night-migrating birds, for example, coincide globally with the most light-polluted regions on Earth (Cabreara-Cruz 2018), and the local-scale attraction of birds to ALAN is well documented (e.g. Cabrera-Cruz 2021), and known to lead to fatal collisions with illuminated structures (Longcore 2018, van Doren et al. 2022). Bats may delay their flights, reduce their commuting activities and suffer habitat fragmentation from illuminated passages, leading to altered flight paths without any signs of adaptation over time (Stone et al. 2009). Although urban spaces have received much attention as areas of concentrated artificial lighting, it is likely that increased incidence of ALAN in remote rural areas, or at sea, will have similar, or even disproportionately large, impacts (Gaston et al. 2021).

Whereas the impacts of ALAN on terrestrial ecosystems are well-researched (for references see above), marine habitats and species have received relatively little attention. Known and potential impacts of marine and coastal ALAN, however, include those on navigation, reproduction and recruitment, predator–prey interactions, and communication across a wide range of species (reviewed in Gaston et al. (2021)). In the last decade, 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 harbours. Lighting at sea can carry far (4.8 km in every direction at human eye level), as the direct light paths are typically only hindered by the curvature of the Earth, and may be exacerbated for moving animals, e.g. for 110 km if these animals fly high at 1000 m above sea level (asl). The effects of direct light emissions are further amplified by (artificial) 'sky glow', the increase in night sky brightness due to scatter of ALAN by atmospheric particles and molecules (Falchi et al. 2016). Sky glow is, among other things, responsible for a reduction of star visibility globally (Kyba et al. 2021), which may result in a critical loss of information for animals using a star compass for navigation (Foster et al. 2018). Shipping and light-enhanced fishing vessels emit light predominantly in a horizontal plane. Importantly, these light sources, therefore, are generally not detected via remote sensing, so their effects are understudied and most likely underestimated. Effects of ALAN from shipping are likely to be significant, ranging from attraction and disorientation at the scale of individual vessels, to shipping lights experienced as irregular pulses confounding orientational and navigational cues at a regional scale (e.g. Gaston et al. 2021, Votier et al. 2023). Although night-time migratory species are particularly affected by marine ALAN (e.g. Hüppop et al 2016), recent studies demonstrate that the behaviour of diurnally migrating species is also affected by ALAN (Burt et al. 2023, Martin & Banks et al. 2023).

We focus specifically on the effects of ALAN associated with increased maritime activity in the North Sea on migratory birds and bats. 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 (Degraer et al 2019, Emeis et al 2015). Human use of this marine space is projected to increase significantly in 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 (see e.g. OSPAR 2023a). We can expect to see a dramatic expansion in the volume and intensity of human activities in the North Sea, as both European and national climate change mitigation policies aim for the accelerated roll-out of offshore renewable energy production. The European Commission's offshore renewable energy strategy (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 eight northern European countries have committed to ambitious targets for the expansion of OWF in the North Seas 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. To date, North Sea coastal states, however, have failed to achieve this status, and the North Sea continues to be in a critical state when measured across a wide range of indicators (see BMU 2019). Conservation efforts will need to shift to ecological restoration on a large scale to ensure the ecological integrity and resilience of the North Sea is not irreversibly compromised. Mobile species perform important ecosystem functions (e.g. regulating prey abundance, delivering nutritional input, production of biomass) to the extent that the conservation of the species movement as an ecological process may be as important as conserving species themselves (Bauer & Hoye 2014, Runge et al. 2014, Cooke et al. 2024). 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), both international agreements within the framework of the Bonn Convention on Migratory Species.

To date, however, marine ALAN has received peripheral attention only within sea-basin level assessments of the impacts of current and future human activities on marine ecosystems (e.g. HELCOM 2023, OSPAR 2023a). The 2023 OSPAR Quality Status Report, for example, recognises 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. While it is noted that attraction to offshore platforms can lead to mortality, affecting a large number of individuals across a range of species, it is deemed that there is currently insufficient evidence for significant population-level effects (e.g. OSPAR 2023b, BSH 2021). Within the relevant grey literature, a comparatively narrow focus on collision risk and habitat loss among birds and bats is evident, with a selective focus on seabirds (e.g. Potiek et al 2021). The prevalence and increasing penetration of ALAN across marine and coastal areas have, however, prompted conservation managers to seek dark(er) sky status for protected areas (Davis et al. 2016, DarkSky International 2024). Yet, given the pervasive nature of ALAN, measures specific to marine protected areas alone are not sufficient. 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, in order to inform decision-making at an early stage in the policy process.

2) Effects of Marine ALAN on Migratory Birds and Bats

The spectrum of artificial light typically ranges from 350-800 nm (Longcore 2018), which corresponds well with the wavelength of maximum absorbance of the photoreceptors of birds (Hart 2001) and bats (Mistry & McCracken 1990, Müller et al. 2009, Gorresen et al. 2015, Voigt et al. 2018). it remains challenging, however, to identify ALAN frequency spectra relevant to various taxa (Marangoni et al. 2022, but see Longcore 2018). For example, most commercial light measuring equipment under-samples low-wavelength (blue to UV) frequencies, which are visible and relevant to birds and bats, with blue light even seeming to be favoured among biological receptors (e.g. Syposz et al 2021, Marangoni et al. 2022). This highlights the importance of proper spectral characterisation of ALAN. Moreover, intrinsic difficulties of identifying and describing the reactions and behavioural adjustments of free-flying bats and birds make assessments of the biological implications of ALAN challenging. Also, information about spectral emissions of commercially available light sources used in the marine sector and on wind turbines is not easily accessible and thus, additional measurements by researchers are required prior to any experimental investigation into animal response behaviour (Voigt et al. 2018). Nevertheless, it has been shown that light characteristics (colour, intensity and blinking mode) influence the degree of attraction among nocturnally migrating birds and bats. For birds, blinking lights are found to be less problematic than coloured lights, and red light leads to less attraction than light of other wavelengths (Rebke et al. 2019, Zhao et al. 2020). In contrast, for bats, a blinking regime appears to make no difference for the phototactic response, i.e. it neither attracts nor repels bats (Jain et al. 2011). The impact of ALAN on bats appears to be generally more complex; in the migration and sea-crossing context, bats not only visually orient for navigation but they may even switch to positive phototaxis to exploit foraging opportunities en route of transit as they are limited in their capacity to use body fat to fuel long migrations (Voigt et al. 2012). However, North Sea crossing pipistrelle species have been observed to increase their flight activity around red as well as green lights, which was unrelated to foraging at a coastal site (Voigt et al. 2017, 2018).

For night-migratory birds (typically small songbirds) and long-distance migratory bats, water bodies such as the North Sea can constitute a significant ecological obstacle, promoting a detoured route along their migratory journeys from northern to southern Europe and Africa. Despite this, the scale of offshore bird migration should not be underestimated, as many landbirds do undertake long overwater crossings (Williamson 1958 Alerstam 1990, Bairlein et al. 2012) including across the North Sea (Shamoun & van Gasteren 2011, Dierschke et al. 2011, Brust & Hüppop 2022). Many individuals moreover land and stop over on Helgoland, a small island in the German Bight (Dierschke et al 2011), where also migratory Nathusius' pipistrelles, well-known bat migrants, are regularly recorded (Seebens-Hoyer et al. 2022). Notably, Rüppel et al. (2023) found that 54% of migrating songbirds from seven species chose an offshore route crossing the German Bight area of the southeastern North Sea rather than a coastal route on spring migration. This relative proportion of offshore vs. onshore crossing birds is species-specific, suggesting varying impacts of the projected increases in offshore artificial structures.

Evidence for this in bats is scarce, and we are only beginning to understand the relevance of offshore routes for this organismal group, but it is certain that bats do perform regular crossings of the North Sea (Ahlén et al. 2009, Hüppop & Hill 2016, Limpens et al. 2017, Bach et al. 2022). Among the approx. 45 species of bats in Europe, all five long-distance migratory species have been recorded there, either at sea on ships and oil rigs or on islands such as Orkney, Shetland and Iceland after crossing the sea (Koopman and Gudmundsson 1966, Corbet & Harris 1991, Speakman et al. 1991). However, many records are considered "ship-assisted" where bats landed on a vessel and have been displaced along the shipping route before being detected. Illuminated objects such as vessels and oil rigs pose sensory traps to bats, as these "lure" them in (Hüppop & Hill 2016). The same can be assumed for wind turbines at sea that are visible to bats beyond their echolocation range through aviation lighting, and which on land also, are exploited as hunting grounds and mistaken as potential roosts (Cryan & Brown 2007, Ahlén et al. 2009, Cryan et al. 2014). Although most bats are recorded flying below 10 m asl, this is attributed to a sampling bias due to technical challenges of recording bats with microphones at critical heights where turbine blades operate (Ahlén et al. 2009, Brabant et al. 2016). Also, bats have been observed to quickly increase flight altitude when obstacles such as wind turbines or lighthouses are present (Ahlén et al. 2009). Nevertheless, bat foraging at sea is a common observation, e.g. when searching for 'grounded' aerial insects that themselves were lured onto sea by phototaxis, (Ahlén et al. 2009). For bats at the North Sea, the most plausible hypothesis to date aiming to explain large numbers of them is that they migrate across the sea to reach the British Isles for hibernation (Speakman et al. 1991). This is supported by phenological data which highlight occurrences of bats at sea and over coastal waters during spring and autumn migration season (Ahlén et al. 2009, Rydell et al. 2014, Hüppop & Hill 2016). However, evidence about which populations from which littoral states are crossing the North Sea more regularly, and where the most important flight corridors run, is mostly missing.

Flights over open water can be challenging for migrating songbirds and bats as landing on the surface of the sea for resting is not an option. This becomes particularly critical, when adverse weather conditions such as strong winds, heavy rain or fog, usually promoting landing (Schmaljohann et al. 2022), suddenly appear. As a consequence, there is a high temporal concentration of migratory movement across the North Sea on a small number of nights in both spring and autumn, as birds seek to avail of favourable weather conditions (e.g. Bradaric et al 2020, 2024). Indeed, reliable predictions of intense migration nights are found to be highly weather-dependent (Bradaric et al. 2020, Manola et al 2020). Although migratory birds may postpone departure under poor weather conditions (Hüppop et al. 2016; Schmaljohann et al. 2022), for birds that do depart, it is likely that adverse weather conditions (in particular overcast skies) contribute substantially to their attraction to artificial light sources (Ronconi et al., 2015, Rebke et al. 2019). Overcast skies could impair the ability of birds to use celestial cues, e.g. for compass orientation, increasing the likelihood of attraction and/or disorientation by artificial lights (Bolshakov et al., 2013; Zhao et al., 2014). For bats, we lack a comprehensive understanding about the circumstances that lead to an impairment of their orientation system for long-range navigation. However, bats may integrate solar cues at dusk for the calibration of their compass system; this has been shown for migratory Soprano pipistrelles in Europe that also occur at the North Sea (Lindecke et al. 2019, Schneider et al. 2023). Further, bats may use the post-sunset glow as a landmark cue for orientation (Buchler & Childs 1982). Both of these mechanisms need to be learned and are vulnerable to ALAN that is potentially in conflict with the natural celestial lighting, particularly under overcast conditions where artificial skyglow is amplified. At sea, this may lead to disorientation or detours taken by bats, yet conclusive data is still lacking.

It is well known that illuminated offshore structures attract night migrating birds (phototaxis) increasing collision risk (Ballasus et al. 2009, Hüppop et al. 2016, Rebke et al 2019). For migratory birds, collision is considered one of the key mortality threats (Loss et al. 2014). Offshore collisions with illuminated structures are mainly reported from lighthouses and light-vessels as well as oil and gas platforms, brightly illuminated ships and research platforms (e.g. Hansen 1954, Wiese et al. 2001, Hüppop et al. 2006, Rebke et al 2019). Whereas collisions with offshore structures appear to be relatively rare, obtaining reliable estimates is notoriously complicated for many practical reasons, e.g., the difficulty accessing remote locations at sea, the vanishing of any collision carcasses in the sea, and technical limitations as one needs elaborated remote-sensing techniques to record collisions (Molis et al 2019). Collision risks and their population effect for larger species, predominantly seabirds, are usually obtained by models, but their inevitable simplification poses significant uncertainty (Cook & Madsen 2019). Concentrations of migrating birds around OWFs have, however, been detected using a range of methods (Hill et al 2014) and thousands of birds have been found to be killed in single incidents (Hüppop et al 2016). One multi-year study found an average of 150 bird mortalities per year at a single platform (i.e. corpses collected on a research platform, excluding those that fell directly into the sea), leading the authors to conservatively estimate overall mortality for the North Sea to be of the order of hundreds of thousands per year (Hüppop et al 2016, see also Brabant et al 2015). Due to their small body-sizes that compromise observations, offshore bat mortality cannot easily be quantified. Yet, onshore data provides evidence of high risks posed by wind turbines particularly to the species that are also reported to migrate across the North Sea (Rydell et al 2010).

To more specifically assess the implications of ALAN, we distinguish between immediate fitness consequences, i.e., death through collision, and delayed fitness consequences, such as orientation impairment either making journeys more energetically inefficient or delaying arrivals at destinations. Marine ALAN impacts on birds are best known among nocturnally active seabirds, where fledglings can become attracted to and grounded by artificial light sources, exposing them to numerous life-threatening hazards, particularly through collisions with structures (Imber 1975, Rodriguez et al 2017). In addition to fatal collisions, migrant responses to ALAN can bias resource availability during stopover. Most evidence for this is however indirect, based on migrant density during nightly departures inferred from weather radar data through machine-learning techniques (McLaren et al 2018, Cabrera-Cruz et al 2019, Horton et al 2023). There are also known cases of migratory and other birds falling out on lighted ships (e.g. GEO 2015), which could lead to further delays or misorientation. Non-lethal consequences of ALAN on the overall navigational process remain unclear, in particular due to the complexity underlying migratory sensory and decision-making processes (Sjöberg et al. 2016, Chernetsov 2017), the challenge in tracking sufficient numbers of migrants precisely across long distances (Nathan et al. 2022), and the difficulty in unravelling intended and flown directions in wind-blown environments (Shamoun-Baranes et al. 2017).

The ultimate consequences of non-fatal ALAN effects are little understood in terms of survival or timing/reproductive performance. It is known, however, that single intense incidents can have significant effects. For example, single intense tourist-related ALAN disturbances reduced nightly chick weight gain in a Mediterranean-breeding seabird, the Scopoli's shearwater (*Calonectris diomedea*), but did not affect weight at fledging (Cianchetti-Benedetti et al 2018). Knock-on ALAN effects due to delays, misorientation or compromised acquisition of resources are similarly unknown, as with ALAN effects on land (McLaren et al 2018, Horton et al 2023). Nonetheless, even brief and local disturbances, such as from firework displays, have been shown to have impacts on birds over many weeks and across tens of kilometres (Kölszch et al 2023, Hoekstra et al 2024).

3) Implications for Policy and Practice

We thus conclude that illuminated offshore structures are likely to have significant adverse impacts on migratory birds and bats. Uncertainties remain regarding the extent to which fitness and mortality impacts can be causally attributed to marine ALAN. Empirical evidence for ALAN impacts at OWFs is furthermore sparse due to difficulties in measurement and access to wind turbines. Consequently, the extent of population-level impacts is 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 planned increases in the overall volume and density of OWFs in the Greater North Sea will, in the absence of mitigation measures, lead to high (and potentially population-relevant) levels of collision-induced mortality and likely lead to significant indirect fitness consequences, impacting on the ability of nocturnally migrating birds to cross the North Sea and complete their migratory journeys safely. To date, however, conservation measures for volant species in the North Sea have focused primarily on seabirds rather than migratory songbirds and bats. This is not surprising, given the critical importance of the southern and eastern North Sea (Wadden Sea) for migratory sea- and shorebirds.

An ecosystem-based approach to marine management and maritime spatial planning requires that in the absence of complete information, a precautionary approach should be adopted. This implies that mitigation measures are 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 that is at the core of EU environmental policy calls for policy-makers to take preventative regulatory action before risks materialise, in order to prevent unnecessary harm (Eckley and Selin, 2004; Tosun, 2013). The 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). In the context of maritime spatial planning, this principle implies that decisions should not only be based on the best available evidence but should favour the conservation of marine ecosystems, where potential negative impacts may be anticipated, but existing scientific studies are insufficient to quantify the extent of such environmental risks (see also Walsh et al 2024, forthcoming).

Options for reducing the risks posed by offshore wind turbines and associated transmission stations to nocturnally migrating birds include optimal siting strategies, whereby migration corridors are avoided, temporary shutdowns, and the selection of the least hazardous forms of lighting (Degraer et al 2023). Since 2023, Dutch authorities have introduced a shutdown protocol for selected North Sea OWFs. The protocol is 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). There are plans to develop similar models for other areas of the Dutch North Sea, encompassing a greater number of OWFs. The predictive accuracy of the model is expected to improve over time as it is trained with new data continuously (Degraer et al 2023). In Germany, mitigation measures are planned for the Baltic Sea coastal waters and Exclusive Economic Zone, but are not currently planned for the North Sea EEZ. The selected mitigation measures for the Baltic Sea are focused on controlling the illumination rather than the operation of the wind turbines. Following this approach, lights will be switched on only when this is necessary for aircraft safety. For the German North Sea, a different approach is adopted, initially focused on monitoring bird flights within OWFs. In a subsequent step, based on the monitoring results, a curtailment strategy with potential application to the German North Sea is to be developed (Degraer et al. 2023). Other North Sea countries have not yet implemented mitigation measures to date.

4) Conclusions

Although future research is needed to advance understanding on a number of questions concerning the direct impacts of marine ALAN on orientational and navigational performance and the precise extent of non-fatal effects over shorter (days) and longer (years) timescales and despite difficulties in access to offshore structures for research purposes, we find mounting evidence of significant adverse impacts of marine ecological pollution on migratory birds and bats. We recommend the further development of an integrated sensory ecology research framework focussed on industrialising marine spaces such as the North Sea as ecologically sensitive areas for songbird, seabird and bat navigation (see Martin & Banks 2023). Further applied empirical studies are needed to assess the likely impacts of current and emerging sources of marine ALAN, from shipping and harbours to OWFs and LNG terminals. In particular, ecosystem-based maritime spatial planning must be informed by robust assessments of the likely cumulative impacts of significantly higher densities of illuminated structures at sea. There is furthermore an evident need for enhanced transboundary cooperation between economic actors, consenting authorities, policy-makers and researchers at the scale of the Greater North Sea, to support sea-basin level cumulative effects assessments.

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[1] Belgium, Denmark, France, Germany, Ireland, Netherlands, Norway and UK. The term North Seas is used to apply to the combined EEZs of these eight countries. Luxembourg is also a signatory of Ostend Declaration although it does not have marine space of its own.