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REVIEW ARTICLE

Cumulative adverse effects of offshore wind energy development on wildlife

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Offshore wind energy development (OWED) is being pursued as a critical component in achieving a low-carbon energy economy. While the potential generating capacity is high, the cumulative effects of expansion of OWED on wildlife remain unclear. Since environmental regulations in many countries require analysis of the cumulative adverse effects (CAE) during permitting processes, this paper reviews the state of knowledge on CAE of OWED on wildlife. We synthesize ecological research on the effects of OWED on wildlife; delineate a framework for determining the scope of CAE assessments; describe approaches to avoiding, minimizing and compensating for CAE; and discuss critical uncertainties.

Keywords: adverse effects; cumulative effects; mitigation; offshore wind farm; wildlife

1. Introduction

Worldwide, governments and industries are looking to increase the production of offshore wind energy. This movement stems from a strong interest in diversifying energy sources, policies aiming to reduce the carbon intensity of global energy production as a way to address climate change, and the need to meet growing coastal demands for electricity. Offshore wind is framed as an energy alternative with lower life-cycle adverse effects to the environment (Ram 2011), yet there are concerns that deployment of thousands of offshore turbines may lead to declines in wildlife populations due to cumulative adverse effects (CAE). Understanding the complexities of the effects of offshore wind energy development (OWED aka wind farm) on wildlife, how they accumulate and whether this accumulation causes population level impacts is a pressing multidisciplinary challenge, since over the next decade OWED is expected to significantly expand in Europe and begin in the United States.

Currently, over 6 gigawatts (GW) of offshore wind energy have been deployed in Europe (EWEA 2013) and globally 77.4 GW are predicted by 2021 (BTM Consult ApS 2012). The waters of 10 European countries contain 58 wind farms and nearly 2000 offshore wind turbines (EWEA 2013). Deployment of OWED in the EU has the potential to expand up to 40 GW by 2020 and up to 150 GW by 2030 (CEC 2008). In the UK, 18 GW could be deployed by 2020 and 40 GW by 2030 (UKDECC 2011). Deployment of offshore wind has yet to occur in the USA; however, the US National Renewable Energy Laboratory (NREL) estimates the potential capacity of offshore wind power in

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the USA as 4200 GW (Lopez *et al*. 2012). The US Department of Energy has set a goal of 54 GW, which would be approximately 5000−8000 turbines in the water, deployed OWED by 2030 (DOE 2011).

While taxa dependent effects to wildlife from OWED are direct (e.g., mortality and injury) or indirect (e.g., general disturbance caused by the turbines and maintenance vessels), and are caused by hazards such as noise from pile driving, boat traffic, and lighting. Yet, the greater concern is how multiple OWEDs, combined with other anthropogenic stressors, will affect wildlife populations through time and space. These CAE are recognized as an important issue for birds (Drewitt and Langston 2006; Fox *et al.* 2006; Masden *et al*. 2010; Langston 2013; Larsen and Guillemette 2007), marine mammals (Dolman and Simmonds 2010), fish (Gill, Bartlett, and Thomsen 2012), and the environment in general (Boehlert and Gill 2010). However, with the exception of several modeling efforts (see Masden *et al.* 2010; Poot *et al.* 2011; Topping and Petersen 2011) and working groups (King *et al.* 2009; Norman, Buisson, and Askew 2007), knowledge of CAE of OWED on wildlife remains relatively unexplored and poorly understood.

Laws in the USA, Canada, the UK, and the EU all require environmental assessments as part of permitting and approval processes. While the exact language differs from country to country, the laws explicitly recognize the accumulation through space and time of human actions that degrade the environment; that an attempt to ameliorate combined adverse effects of those actions should be made; and that mitigation measures may be necessary when effects are unavoidable. Thus, these countries' decision makers are required to consider the incremental and CAE of anthropogenic actions on the environment and the potential alternatives to those actions (CEQ 1997; Hyder 1999; Hegmann *et al.* 1999; Cooper 2004). Therefore, there is a critical need to better understand CAE from not only a scientific perspective, but also a regulatory or legal perspective.

In this paper, we review the state of the knowledge on CAE of OWED on wildlife. Throughout, we will use the term "cumulative adverse effects" or CAE. We will use this in place of the terms "cumulative effects" or "cumulative impacts" that are used in laws and regulations as well as academic papers. Broadly defined, CAE is the accumulation of adverse effects over time and space. We begin with a synthesis of ecological research on the direct and indirect effects of OWED. We then focus in on CAE, explaining what is encompassed in CAE and the importance of CAE. Next we delineate a framework for determining the scope of CAE assessment. We then discuss mechanisms for alleviating CAE and critical uncertainties influencing progress. This leads us to a discussion on how a collaborative stakeholder process could address ongoing policy challenges.

2. Effects of OWED on wildlife

2.1. Factors leading to the CAE of OWED (project components and species-related)

Prior to investigating the CAE of OWED on wildlife, it is useful to review the adverse effects of specific elements of offshore wind projects on wildlife. Such adverse effects are a function of the physical hazards of OWED, species' vulnerability (behavioral and life history attributes), and exposure (duration and the geographic extent to which wildlife interact with OWED) (modified from Crichton 1999; Kinlan, Rakin, and Caldow 2013; Williams *et al.*, forthcoming). Recognizing that the terms hazards, vulnerability, and exposure are nuanced and have been applied in a variety of manners, we define the terms as used in this paper below.

The OWED hazards present to wildlife are the changes in environment caused by the project components (i.e., turbines and network connections) during each development phase (pre-construction, construction, operation, and decommissioning) (modified from Williams *et al.*, forthcoming), also described as "impact-producing-factors" (BOEM 2012; DOE 2013). The primary hazards are as follows: seismic surveys during pre-construction; support structure building (fixed bottom and floating), trenching for electrical cables, and constructing cable landfall during construction; the physical space occupied by the turbines and the entire OWED, as well as the electromagnetic fields (EMFs) emitted from cables during operation; and yet-to-be determined decommissioning activities (Table 1). The state of knowledge on the adverse effects of OWED support structures on wildlife is primarily focused on the noise generated by pile-driven monopiles. The construction of other types of fixed-bottom support structures will generate less noise: gravity-base structures will have no pile driving; the piles of jacket-support structures are substantially smaller and thus have less noise generated during pile driving, and in hard soils can be inserted into pre-drilled holes. While the adverse effects of floating offshore turbines on wildlife is poorly understood, wildlife response may differ for slack or tension mooring systems that are tethered to the seafloor with embedded anchors, piles, or gravity bases. Seafloor preparation and decommissioning will also be different with these alternate support structures (J. Manwell, personal communication, 2014). Exposure to wildlife will also be influenced by turbine spacing, which is determined by turbine size (Manwell 2009). As more efficient/larger turbines are developed, turbines will need to be placed further apart, increasing the footprint of the OWED. How wildlife will respond to increased spacing has yet to be studied. During all operation phases, increased boat traffic and lighting present additional hazards.

A species' vulnerability is determined by the likelihood an individual will interact with, and respond to, an OWED and that the response will adversely affect the population (modified from Furness, Wade, and Masden 2013; Garthe and Huppop 2004). As such, vulnerability overlaps with what some refer to as "meso- and micro-exposure" (Burger *et al.* 2011). Our use of the term vulnerability does not encompass whether or not the

Table 1. Primary OWED hazards to wildlife: cause.

Development phase	Development component	Hazard source	Hazard
Preconstruction	Turbines	Seismic profiling	Noise, pressure
	Network connection	Seismic profiling	Noise, pressure
Construction	Turbines	Pile driving	Noise, pressure, turbidity, sedimentation, physical alteration of habitat
	Network connection	Trenching	Turbidity, sedimentation, physical alteration of habitat
Operation	Turbines	Turbines, wind farm footprint, mooring lines	Disturbed air space, turbulence, noise, permanently altered habitat
	Network connection	Electrical cable	EMF
Decommissioning	Turbines	Decommissioning activities	Unknown
	Network connection	Decommissioning activities	Unknown
All phases	All components	Boat traffic, lighting	Disturbed marine habitat, noise, turbulence, light

species' is *a priori* more at risk as may be reflected by the species' conservation status (Furness, Wade, and Masden 2013); rather, the level of a species' vulnerability depends upon behavioral traits of the species that increase its interaction with OWED during breeding, foraging, and migrating. Once an individual encounters an OWED, the behavioral response can either be an attraction or avoidance (macro and micro scales). A species' vulnerability also depends on its life history and to what extent adverse effects from individual responses to an OWED will lead to demographic change (see Furness, Wade, and Masden 2013; Garthe and Huppop 2004).

Exposure refers to frequency and duration by which individuals interact with OWED over a specific geographic area (modified from Williams *et al.*, forthcoming). An increase in the number of OWEDs will result in an increase in the exposure of a vulnerable species to the hazards posed by OWEDs.

2.2. Adverse effects by taxonomic class

Adverse effects of OWED on wildlife vary by taxonomic group and offshore wind energy development phase (Williams *et al.*, forthcoming). The primary adverse effects for all species are direct effects from OWED hazards that cause injury or death; indirect effects of behavioral response (attraction and avoidance) to the turbine construction and operation; and/or changes in habitat from all development phases (see Fox *et al.* 2006; Drewitt and Langston 2006). The OWED hazards most likely to cause adverse effects to fish, sea turtles, and marine mammals are seismic surveys during pre-construction; pile driving during construction; and submerged infrastructure present during operation. The OWED hazards most likely to cause adverse effects for birds are the rotors and the project's footprint, whereas bats will likely be most affected primarily by the turbines (Table 2). The specific effect will vary by a species' life history. Below, we delineate more specifically the adverse effects of OWED on fish, sea turtles, marine mammals, and birds. As these effects have not been studied comparatively, we describe effects documented by empirical research yet do not provide a relative ranking of adverse effects.

Fish within a close proximity to pre-construction and construction activities will be exposed to noise and pressure hazards. Pre-construction geophysical seismic surveys that use air guns can lead to the direct effect of fish and egg mortality. The surveys may also displace individuals, which can have the indirect effect of localized changes in fisheries (Hirst and Rodhouse 2000). During construction, the hazard of noise from pile driving may cause a decrease in clupeid abundance from the direct effect of injury and mortality (Perrow *et al.* 2011) as well as hearing loss in fish (Kikuchi 2010); the construction of alternate types of support structures, such as gravity bases or jackets, will generate substantial less noise and pressure. The turbidity and suspension of sediment from construction of foundations and cable trenching may have indirect effects by causing localized changes in habitat and food resources (Michel 2013; Michel *et al.* 2007). Indirect effects during operation may include changes in habitat caused by scour protection at the turbine's base. The changes in habitat may lead to regime shifts (Burkhard and Gee 2012) and changes in the biodiversity of the benthic community (Lindeboom *et al.* 2011); fish aggregations from reef effects (Boswell *et al.* 2010; Inger *et al.* 2009; Linley *et al.* 2007); and localized behavioral response to operational sound (Kikuchi 2010) and EMF emitted from electric cables (Gill, Bartlett, and Thomsen 2012; Boehlert and Gill 2010). Research has not conclusively determined if effects during different development phases and from components will affect population trends, but the composition of the ecosystem in the immediate vicinity of the OWED will likely change.

Table 2. Primary adverse effects of OWED hazards to wildlife: effect.

Taxon	Vulnerable characteristic	Vulnerable life stage	Primary exposure	Adverse effect
Fish	Sensitive to habitat alterations, EMF, and noise; present at all OWEDs	All	All	Mortality, injury, displacement, habitat alteration, reef effect
Sea turtle	Sensitive to EMF and noise; inability to escape boat hazards; widespread abundance	All but nesting	All	Mortality, injury, behavioral alteration
Marine mammal	Long-lived/high adult survival/low annual reproductive rate; widespread abundance; sensitive to sound; inability to escape boat hazards	All	Construction	Mortality, injury, hearing damage from noise, behavioral alteration
Bird	Long-lived/high adult survival/low annual reproductive rate; fly at rotor height; attraction to and avoidance of turbines	Breeding, migrating, wintering	Operation	Mortality, injury, displacement
Bat	Long-lived/high adult survival/low annual reproductive rate; attraction to turbines	Migrating	Operation	Mortality

Little is known about the effects of OWED on sea turtles. The hazard of increased vessel traffic during all phases of development may have the direct effect of higher rates of turtle/boat collisions. Pre-construction activities, such as geophysical surveys, may have direct localized effects of hearing damage and indirect effects such as behavioral changes (MMS 2007). During construction, due to their inability to avoid construction equipment, hatchlings may be at greater risk of direct mortality from pile driving and trenching (MMS 2007). If explosives are used during construction or decommissioning, turtles may be killed or injured (Continental Shelf Associates 2004). Although light is known to affect sea turtle behavior (Salmon 2003), how adult and juvenile sea turtles will respond to lit construction vessels and turbines is poorly understood.

Similarly, marine mammals may be adversely affected during all stages of OWED. Pre-construction surveys that generate noise can directly affect marine mammals by causing hearing damage and injury and indirectly affect them by causing behavioral responses (MMS 2007). These adverse effects can also be caused by noise generated by pile driving during OWED construction (McCann 2012; David 2006; Madsen *et al.* 2006), but species could have different responses and there remains uncertainty on the effects of pile driving on marine mammals (Thompson *et al.* 2010). Additionally, little is known about how marine mammals will respond to the mooring lines of floating turbines, which could create a collision hazard. Seals can be temporally displaced from haul-out sites from pile-driving noise during construction, though to date, no long-term effects have been found (Edren *et al.* 2010). Once constructed, the effect of the turbines is more uncertain. Porpoises have been displaced from OWEDs (Tougaard *et al.* 2005), but may habituate to the turbines, or the reef effect may provide an increase in prey availability (Teilmann, Tougaard, and Carstensen 2012). During operation, the physical structure of the turbines and the noise generated by the turbines may cause cetaceans to avoid the OWED and thus indirectly result in the loss of feeding and mating habitat, and disrupt migratory routes. Floating turbines may lead to fewer indirect effects; however, there could be direct effects if marine mammals collide with mooring lines. Decommissioning activities are not expected to have significant adverse effects (MMS 2007). Vessel traffic during any stage of OWED can increase the opportunity for a marine mammal/boat collisions (McCann 2012) which can cause direct mortality (Allen, Angliss, and Wade 2011; Waring *et al.* 2009) during all development phases. Since large cetaceans are generally absent around operating OWEDs in the UK and Europe, actual effects on large cetaceans will not be fully understood until OWEDs are built in the USA.

Turbine operation is likely the primary cause of adverse effects on birds. Pre-construction and construction activities are poorly studied, yet since they have lower direct impacts and temporally limited indirect impacts, they are expected to result in fewer adverse effects. Decommissioning activities are expected to have "negligible" effect on birds (MMS 2007). Fox *et al.* (2006) describe three factors that lead to adverse effects during operation of OWED: direct effects of collision mortality; indirect effects of avoidance response; and physical habitat modification. Collisions generally occur in two ways: birds collide with the superstructure or rotors during operation or birds are forced to the ground due to the vortex created by the moving rotors (Drewitt and Langton 2006; Fox *et al.* 2006). While an estimated 573,000 birds are killed a year at terrestrial wind farms in the USA (Smallwood 2013), few direct mortalities have been observed at OWED sites (Petersen *et al.* 2006; Pettersson 2005), with the notable exception of a coastal wind project located directly adjacent to a tern colony in Belgium (Everaert and Stienen 2007). The dearth of empirical evidence on direct mortality may reflect actual low mortality rates, or it may result from methodological challenges in detecting bird fatalities at OWED sites and a lack of extensive post-construction collision studies.

In terms of displacement of birds, while OWED may invoke an avoidance reaction from some species, it may attract or cause no change in behavior in others (Krijgsveld *et al.* 2011; Lindeboom *et al.* 2011; Fox *et al.* 2006). Detecting avoidance response is stymied by challenges in conducting pre- and post-construction studies that have enough statistical power to detect a significant change (Maclean *et al.* 2013; Lapena *et al.* 2013). Nonetheless, avoidance responses have been documented for many species of waterbirds (Plonczkier and Simms 2012; Desholm and Kahlert 2005; Percival 2010; Lindeboom *et al.* 2011). Initial avoidance may cease several years after construction as food resources, behavioral responses, or other factors change (Petersen and Fox 2007; Leonhard *et al.* 2013). Birds that avoid the area completely experience a *de facto* habitat loss (Langston 2013; Drewitt and Langston 2006; Masden *et al.* 2009; Petersen *et al.* 2011).

Little is known about how bats will respond to OWEDs during any development phase. Bats are present in the offshore environment in both Europe (Ahlen, Baagoe, and Bach 2009; Boshamer and Bekker 2008) and the USA (Cryan and Brown 2007; Johnson, Gates, and Zegre 2011; Grady and Olson 2006; Pelletier *et al.* 2013; Hatch *et al.* 2013), and have recently been detected at an OWED in the Netherlands (Poerink, Lagerveld, and Verdaat 2013). In the USA, the bats detected offshore have primarily been migratory tree bats (Cryan and Brown 2007; Grady and Olson 2006; Hatch *et al.* 2013). At terrestrial wind projects in the USA, 880,000 bats are estimated to be killed annually (Smallwood 2013) from direct collision mortality and barotrauma (Cryan and Barclay 2009). These fatalities, which affect predominantly migratory tree-roosting bats (Kunz *et al.* 2007), may occur when mating bats are attracted to turbines (Cryan 2008). Thus, collision mortality during operation of OWEDs is the most likely direct adverse effect. Effects of decommissioning are unknown but are likely insignificant.

3. Accumulation of adverse effects of OWED on wildlife

Most research has focused on the effects of a single OWED on wildlife. However, given the scale of projected future deployment of OWED, many authors raise the concern that the effects from a single OWED could accumulate over multiple projects (see Langston 2013; Masden *et al.* 2009; Fox *et al.* 2006; Drewitt and Langston 2006; Gill, Bartlett, and Thomsen 2012; Larsen and Guillemette 2007; Dolman and Simmonds 2010; Masden *et al.* 2010). CAE refers to the combined effects of multiple anthropogenic actions through space and time (MacDonald 2000); it represents a metric of total human impact to the ecosystem. First, the fitness of an individual in a population is reduced via its interaction with a hazard posed by OWED. Second, the effects of multiple OWED on that individual and others accumulate into population level declines (Figure 1). In this section, we focus solely on how the presence of multiple OWEDs may result in CAE. Then, in Section 4, we discuss a broader conceptualization of CAE, which includes anthropogenic hazards beyond OWED.

While scholars vary in the manner in which they categorize adverse effects (Hyder 1999; Cooper 2004; CEQ 1997; Bain *et al.* 1986; MacDonald 2000; Crain, Kroeker, and

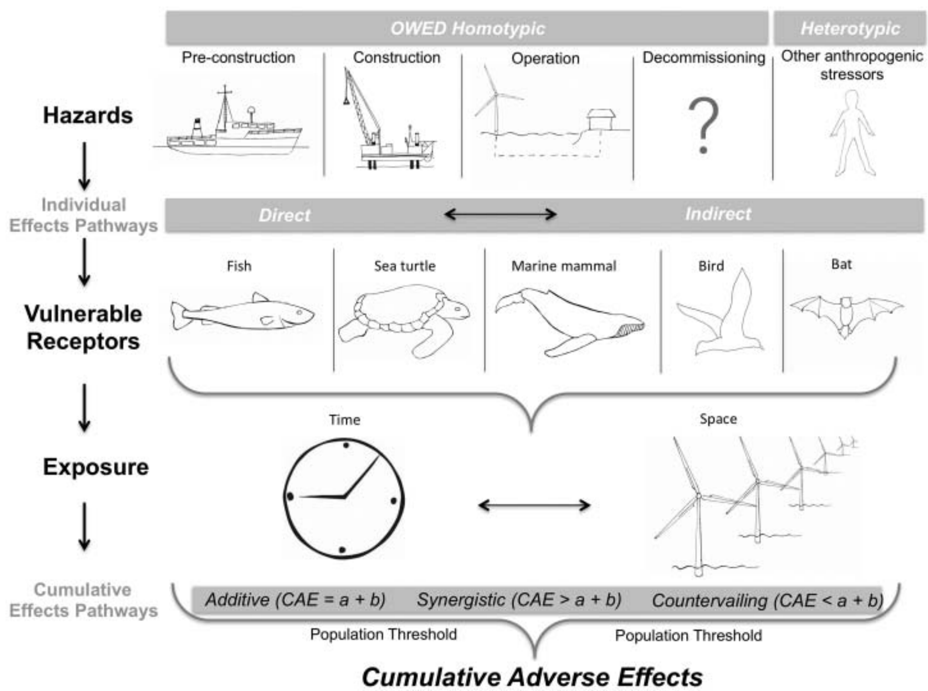

Figure 1. The process of the cumulative adverse effects of offshore wind energy development on wildlife. Homotypic OWED hazards, as well as other heterotypic sources, directly/indirectly adversely affect vulnerable receptors. These adverse effects accumulate as vulnerable receptors are repeatedly exposed through time and space to the OWED hazards via additive, synergistic, and countervailing pathways. The adverse effects of the exposure of vulnerable receptors to OWED hazards can then accumulate to a degree that a population threshold is passed.

Halpern 2008) and a dominant typology has yet to be developed, adverse effects on an individual can occur primarily through direct and indirect pathways (hereafter, referred to as effects pathways). Direct effects are the result of a stimulus−response relationship (Canter and Kamath 1995; Bain *et al.* 1986), meaning that there is a clear cause−effect relationship between the effects on wildlife and an anthropogenic action such as mortality from colliding with a turbine. Indirect effects are second- or third-level effects, and occur away from the project or through multiple effects pathways (Hyder 1999). For example, fish abundance could increase due to a *de facto* fishing exclusion zone at an OWED; this abundance of fish might attract additional birds, which in turn could change the number of collision mortalities.

Adverse effects on individuals can combine interactively causing CAE and thus population level declines. Interacting effects are sometimes referred to as multivariate effects (Bain *et al.* 1986). Interacting effects may be additive (CAE = a + b), synergistic/supra-additive (CAE > a + b), or countervailing (CAE < a + b), where "a" and "b" represent the effects of separate actions (adapted from Crain, Kroeker, and Halpern 2008; Irving *et al.* 1986; Canter and Kamath 1995; CEQ 1997). Effects are likely to be additive for long-lived/low-productivity species that experience mortality from multiple OWEDs (Drewitt and Langston 2006) or for wildlife that expend additional energy to avoid multiple wind farms within a migratory corridor (Masden *et al.* 2009).

Irrespective of the interaction mechanisms, the primary concern is that even when the individual effects of separate actions (a and b above) are below a threshold of harm, CAE may exceed the amount a population can withstand and still remain viable. While, as described in Section 2, we have some basic expectations regarding the potential adverse effects of OWED on individual wildlife, in-depth understanding of how those effects translate into population level effects is confounded by significant information gaps (Williams *et al.*, forthcoming). A paucity of knowledge on the demographic patterns that shape population dynamics confounds the delineation of population baselines. In particular, for many species there is a lack of knowledge on population trends and vital rates (e.g., adult survival), as well as how OWED will affect factors regulating and limiting the populations.

More research has focused on the CAE of OWED on birds than other taxonomic classes. Existing analyses of demographic changes to some species of birds have found little evidence of population-level CAE via direct collision mortality (Poot *et al.* 2011), displacement (Topping and Petersen 2011), and cumulative habitat loss due to displacement (Busch *et al.* 2013). Yet not all future build-out scenarios and species of birds have been assessed. Moreover, for other species and taxonomic classes, basic natural history information on when they may be exposed to OWED hazards and information on micro and macro avoidance rates is lacking. Improving knowledge of the CAE of OWED is complicated by the migratory nature of some species, which are only exposed to OWED during a portion of their life cycle, and by the fact that direct effects such as collision mortality may be significant yet rare, and therefore is hard to measure. As explained below, knowledge of baseline and wildlife responses is essential not only for assessing CAE, but also for development of mitigation strategies.

4. The scope of CAE assessments of OWED on wildlife

Conceptually, CAE is all encompassing: it includes all effects from all anthropogenic stressors on all species, with no spatial or temporal constraints. Yet, in practice, every effect and interaction cannot be understood or analyzed. Limitations of data, analytical methods, resources to conduct assessments, and an understanding of how effects interact constrain the extent and depth of the analysis. A critical step to move from a theoretical discussion of CAE to an applied analysis via an environmental impact statement is to define the scope of assessments.

Through the turn of the century, CAE was not well represented in environmental assessments (Baxter, Ross, and Spaling 2001; Burris and Canter 1997; Cooper and Canter 1997; Cooper and Sheate 2002) and the need for greater guidance on CAE assessments was well recognized (Cooper and Sheate 2002; Piper 2001; Canter and Kamath 1995; MacDonald 2000). Governments and academics throughout Europe and North America devised CAE analysis guidelines for environmental assessment regulations (Hyder 1999; Hegmann *et al.* 1999; CEQ 1997; Cooper 2004). While these guidance documents are non-binding, they provide recommendations for conducting CAE assessments, including determining source, spatial, and temporal scope. Nonetheless, even after development of these guidelines, CAE assessments continue to be challenged in court for having an inadequate analysis scope (Smith 2006; Schultz 2012).

While the guidelines developed for CAE assessment provide a general framework that could be used for any environmental assessment, they do not provide sufficient recommendations on how to address issues specific to OWED and wildlife. Development of a guidance document designed expressly for the OWED industry has been recognized as a critical need in the UK (Renewable UK 2011; 2013). Guidelines would provide an applied CAE definition, assessment procedures, and expectations for how CAE assessments are presented in environmental impact statements (Ma, Becker, and Kilgore 2012). This guidance could complement US Bureau of Ocean Energy Management's (BOEM) current efforts to develop recommendations for environmental surveys at proposed OWEDs.

As per the work in Europe by King *et al.* (2009), Masden *et al.* (2010), and others, three inter-related elements that need to be included in an OWED-specific guideline on scoping the CAE of OWED on wildlife are as follows: identification of hazards; evaluation of species' vulnerability, including baselines, effects pathways, and effects thresholds; and delineation of exposure, including spatial and temporal boundaries.

4.1. Identification of hazards

4.1.1. Understanding the source

CAE result from a variety of anthropogenic stressors. These stressors may be homotypic, i.e., multiple developments of the same type, or heterotypic, i.e., multiple developments of different types (Irving *et al.* 1986). Adverse effects of OWED are not isolated from other anthropogenic stressors and CAE sources for any given species are likely heterotypic, including but not limited to aquaculture, fishing, linear infrastructure, shipping, military activities, dredging, gravel mining, fossil fuel extraction, pollution, and climate change (MMS 2007; Renewable UK 2013). Accounting for all anthropogenic stressors and understanding how one OWED may incrementally contribute to existing adverse effects is difficult if not impossible. Beyond qualitative assessments, heterotypic source effects have been addressed through proxies, such as existing species management plans, established viable population levels, maximum sustained harvest, or an established trend trajectory. In those cases, heterotypic source effects are accounted for via the population targets, which have theoretically taken into account other stressors on the population (see below discussion on thresholds). Another approach to managing heterotypic sources has been to use ecosystem-based management and ocean zoning that incorporates the adverse effects from multiple sectors into decision making (Halpern *et al.* 2008).

4.1.2. Understanding the effects pathway

As explained above, the CAE of multiple OWEDs can be additive, synergistic, or countervailing. A lack of empirical evidence on the interactions between adverse effects impedes accurate assessment of CAE. Given these uncertainties, a simplified approach is to assume that effects are additive, while recognizing that interactive effects are likely to occur. (Masden *et al.* 2010).

4.2. Evaluating species' vulnerability

4.2.1. Refining the receptors

While all species that come into contact with OWED will be affected in some manners (Hegmann *et al.* 1999; Canter 2012), practically understanding CAE requires focused inquiry into the most sensitive receptors, defined as "any ecological or other feature that is sensitive to, or has the potential to be affected by, an action" (Masden *et al.* 2010, 2). A receptor is also sometimes called a valued ecosystem component (Hegmann *et al.* 1999). Assessment of CAE of OWED on wildlife thus would focus on species known to be vulnerable to the hazards posed by OWEDs (see Furness, Wade, and Masden 2013; Garthe and Huppop 2004; Desholm 2009; Willmott, Forcey, and Kent 2013). The actual species to be included in the assessment will depend on the geographic location of the project and should be selected based upon being listed as a species of concern, being present in an OWED during critical life stages, having behavioral traits that increase exposure, having been detected in protected areas adjacent to a proposed OWED (Masden *et al.* 2010; King *et al.* 2009), or being important to stakeholders (Hegmann *et al.* 1999). Focusing analysis on vulnerable receptors will serve both to understand the adverse effects on species expected to be most vulnerable to OWED hazards, as well as provide insight into how similar species may be affected.

4.2.2. Having clear baselines

Once the receptors have been defined, a baseline needs to be determined for each. A baseline is a metric that describes the state of the receptor prior to the implementation of OWED. Often, population level is used as a baseline metric. A decline of population levels post implementation of OWED relative to the baseline could indicate an adverse effect of the OWED on the receptor. Due to variation in a species' presence over time and over space, determination of the baseline is not straightforward. In many cases there are neither current nor historic data on species abundance in the offshore environment at a particular location (Pelletier *et al.* 2013; BRP 2006; Geo-Marine Inc. 2010; Langston 2013; Thompson *et al.* 2010). In the absence of a historic baseline, monitoring trends can be used to measure the effects of OWED on wildlife (Hyder 1999; Canter 2012; Masden *et al.* 2010; Cooper 2004).

4.2.3. Stating a threshold

Implicit in measuring CAE against a baseline, or in monitoring population trends, is the premise that there exists a threshold of adverse effects that should not be exceeded. This threshold will vary from receptor to receptor, depending on the species population dynamics. For example, for species that are rare, long-lived, and have low annual reproduction, the loss of one individual may cross a critical population threshold. Conversely, for species that are common, short lived, and have high annual reproductive output, the loss of several hundred or even a thousand individuals might not cause a decline in the global population.

4.3. Delineation of exposure

4.3.1. Determining temporal boundaries

The temporal boundary is a critical element in understanding CAE. Three aspects of the temporal boundary include the following: (1) the duration of sustained adverse effects on the receptor, which can be measured via the lifespan of the project from preconstruction through decommissioning (Hegmann *et al.* 1999); (2) past, present, and future anthropogenic actions that incrementally contribute to CAE (MacDonald 2000); and (3) the life history traits of a receptor that dictate the seasonal and life stage when a receptor is exposed to the action (Masden *et al.* 2010).

4.3.2. Determining spatial boundaries

Like temporal boundaries, spatial boundaries are an important component to understanding CAE, and include the interplay of a biologically relevant geographic unit (e.g., species range, watershed, or ecoregion) and a geographic development envelope (e.g., geopolitical boundaries or an area developed homotypically). Collectively, this creates the spatial area within which a new action is considered along with other anthropogenic actions affecting the receptor. For the biological spatial unit, Masden *et al.* (2010) specify that the following should be considered: spatial scale of the population being affected (i.e., local, regional, or global); how the population is using the space (e.g., sub-population or entire population); at what life stage the birds are interacting with the project (e.g., migration, breeding, wintering); and the area in which the effect will actually occur. Regarding the development area, MacDonald (2000) suggests that for policy decisions, large-scale assessments are most useful, and for project decisions, a smaller area should be considered. Canter and Kamath (1995, 330) recommend boundaries be based upon “natural interrelationships between biophysical environment features, man-generated interrelationships between socioeconomic environment features, and the geographical locations of expected impacts.”

The elements discussed above describe the primary elements to include in scoping guidelines, but would require further refinement and detail. Formalized guidelines would provide consistency and parity between projects, and would facilitate incorporation of project-based assessments into regional decision-making. Guidelines would also provide certainty for developers on the assessment and mitigation permitting requirements.

5. Mitigating the CAE of OWED on wildlife

A principal reason for CAE assessment is that through analyzing the potential adverse effects of OWED, mitigation mechanisms can be identified. Mitigation includes avoidance of adverse effects through siting, minimizing the adverse effects when they cannot be avoided through management, and compensating for adverse effects by replacing losses or reducing other anthropogenic stressors. Implementation of mitigation is a challenging policy problem because it requires identification of cause–effect relationships, assignation of responsibility for action, and the selection of a location for compensatory measures.

Avoidance and minimization of adverse effects begin by addressing the direct and indirect effects of individual OWEDs (see Drewitt and Langston 2006; Cook *et al.* 2011). Avoidance entails siting OWEDs away from high biological productivity areas of the ocean that are critical habitat for wildlife as well as significant migratory routes. To do so requires both an understanding of how oceanographic features are related to wildlife concentrations (e.g., bathymetry, upwelling areas, and confluence of currents) and where those areas are located. Baseline natural resource surveys can inform efforts by regional decision making entities and government agencies to direct development away from these areas. Minimizing the direct and indirect effects at a project level requires consideration of OWED design (e.g., layout and turbine spacing), changes to turbine design (e.g., size, paint schemes, blade technology, lighting, support structure), use of different operational methodologies (e.g., timing of construction, bubble nets, support vessel travel speed, blade cut-in speed, curtailment during migration), and implementation of adaptive management (e.g., curtailing turbines that are causing the greatest adverse effects).

When adverse effects due to OWED cannot be avoided, or sufficiently minimized, mitigation can include compensation. Examples of compensation include protecting or expanding existing breeding habitat, such as seabird nesting islands; reducing mortality of adults of long-lived species, such as in marine mammal boat collisions or fisheries by-catch (birds, sea turtle, non-target vulnerable fish species); or controlling pollutants such as mercury that reduce reproductive success. Whereas many of these compensatory actions may be merited for reasons unrelated to the OWED, and may in fact already be underway, the premise of compensation as a form of mitigation is that it would be designed and implemented to counteract the specific additional effects caused by a particular OWED. While “no net loss” is often a criteria for determining the scope of compensatory mitigation, lags in implementation can lead to a net habitat loss over time (Bendor 2009). Therefore, mitigation will require careful consideration of the temporal nature of impacts and sustained monitoring of mitigation measures to ensure compensation is truly achieved.

The ideal location of compensatory actions will vary by species and by OWED project. In some instances, it may be appropriate for compensation to occur a significant distance away from the hazard. For example, when adverse effects occur within a migratory pathway, compensation near the OWED hazard might be ineffective because there are few mechanisms that could enhance individual survivorship or increase reproductive success at the project site. Yet losses could potentially be compensated for hundreds of kilometers away by enhancing resources at breeding sites to increase reproductive success or by reducing non-OWED hazards near breeding sites and improving individual survivorship. The European Commission *Guidance document on Article 6(4) of the ‘Habitats Directive’ 92/43/EEC*, recommends compensation should (1) occur within the same biogeographic or within the same range, migration route or wintering area for bird species, (2) create the same ecological structure and functions as those lost, and (3) be designed to avoid jeopardizing other conservation objectives. Ideally, compensation is considered first at the project site, second outside of the site but within a common topographical or landscape unit, and third in a different topographic or landscape unit (European Commission 2007).

Given current understandings and technical expertise, predicting adverse effects and measuring the effectiveness of mitigation measures subsequent to their implementation is not yet a reality. Challenges exist particularly with respect to compensation; hence Bronner *et al* (2013) argue avoidance and minimization should be prioritized. In the marine system, compensation often entails creating habitat for species or ecosystem services that were not originally adversely affected by the original action but are important to stakeholders (Levrel, Pioch, and Spieler 2012). Compensatory actions thereby are not always effective in replacing lost ecological resources (Bronner *et al.* 2013; Doyle and Shields 2012), and sometimes replication does not succeed (Brown 2001).

A lack of strong evidence between cause (OWED hazards) and effect (population declines) impedes attribution of adverse effects (direct, indirect, or cumulative) to a particular OWED, subsequently hindering management of CAE. If the hazards of a proposed OWED cannot be linked to expected population declines, or the benefits of mitigation measures cannot be satisfactorily demonstrated, it is difficult for responsible statutory agencies to institute regulatory or policy measures to deny siting at a particular location or to compel a developer undertake costly mitigation measures.

6. Critical uncertainties

Despite the above-described progress towards understanding the effects of OWED on wildlife, a number of uncertainties remain that plague assessment and mitigation activities. While scientific uncertainties arising from incomplete understandings of cause–effect relationships leading to adverse effects are critical barriers, uncertainties in policy processes also hinder progress. These uncertainties are connected in that reducing scientific uncertainties is reliant upon collection, sharing, and analysis of data, the responsibility for which remains distinctly unclear. Moreover, both improved understandings of cause–effect relationships and governance processes are needed to attribute responsibility for mitigation actions.

As described above, major limitations to determining these cause–effect relationships arise from significant data gaps. Knowledge of basic parameters, such as population levels, trends, and vital rates, confounds delineation of baseline populations and determining rates of population decline. Thus, there is a paucity of information on baseline conditions (Smith 2006). Data from monitoring that can be used to iteratively assess CAE (Schultz 2010) could help improve the knowledge base. Yet responsibility for data collection, species monitoring, data sharing, and analysis needs to be clarified (Piper 2001).

From a policy perspective, a key issue is attribution of responsibility for collecting, storing, and analyzing the data on the multiplicity of stressors and receptors to be included in CAE assessments. There are financial and technical constraints to what a single OWED developer can achieve (Piper 2001). Moreover, the data needed for a CAE assessment may be proprietary and not publically available or compiled. As such, it is also difficult for a single developer to incorporate consideration of the impacts of other potential projects into a CAE assessment. This points to the need for regional efforts by government, or non-government organizations that compile information. Such efforts could both increase the ability of scientific studies to improve understandings of effects pathways and improve decision-making by enabling regulators to conduct regional assessments of the interactions across multiple OWED projects.

Collaborative governance processes, private–public partnerships, and stakeholder processes have emerged to engage with these unanswered questions regarding the uncertainty of cause–effect relationships and attribution of responsibility. These processes move towards a "pragmatic approach" of CAE assessments as described by Parkins (2011). The pragmatic approach depolarizes decision-making and is grounded in deliberative democracy where all participants engage in rigorous debate and are willing to revise their position. This is in contrast to the common form of cumulative effects assessments dominated by either a "technocratic approach" that is focused on analytical, data driven modeling, or the "decisionistic" approach in which influential players make unilateral decisions based upon their own political interests (Parkins 2011). A pragmatic approach would also allow for a broader integrated risk analysis that incorporates the climate change mitigative qualities of OWED and the adverse effect from fossil-fuel energy decision-making (Ram 2011). Examples of such approaches include the multidisciplinary stakeholder processes of the Collaborative Offshore Wind Research into The Environment (COWRIE) and the Strategic Ornithological Support Services (SOSS) in the UK, We@Sea in Europe, and the National Wind Coordinating Committee (NWCC) in the USA. Each of these processes has brought together developers, regulators, and NGO leaders to identify and respond to key environmental issues around wind projects. Bringing together this group of stakeholders has changed the nature of regulatory processes, shifting the emphasis from who/which OWED is responsible to what the OWED community as a whole can do to reduce CAE. These groups reduce uncertainty for the regulated community and seek to minimize CAE of OWED to wildlife by establishing best practices (see Drewitt and Langston 2006); agreeing on assessment scope via early dialog between stakeholders and the government (Renewable UK 2013); facilitating the sharing of data collected at particular projects; focusing research on critical information gaps; and determining reasonable mitigation measures.

7. Discussion

If countries in the USA and Europe meet their 2030 goals for offshore wind energy, thousands of turbines in coastal and offshore waters will be deployed. This future build-out is likely to have adverse effects on wildlife. In the above review, we explained that the direct and indirect effects of OWED on wildlife are a function of hazards (changes to the environment by OWED), vulnerability (the likelihood a species will interact and respond to an OWED), and exposure (the duration that individuals interact with OWED over a specific geographic area). These individual adverse effects accumulate additively, synergistically, or in a countervailing manner through an increase of spatial and temporal exposure. To prevent population declines, it is essential that we develop effective practices for the assessment and mitigation of these CAE.

Yet our review and analysis of the assessment of CAE of OWED on wildlife illuminates a number of inter-related challenges with assessment and compensatory mitigation of CAE. Insufficient baseline and wildlife response data impede identifying effects pathways and accumulation resulting from both homo- and heterotypic hazards and their interactions. Technology and financial limitations (e.g., detecting collision mortality of birds and bats over the open ocean) constrain determination of direct effects. Identification of indirect effects (e.g., reduced individual fitness from avoidance response leading to lower reproductive success) is hampered by the fact that such effects may be separated spatially and temporally from an OWED project. Moreover, since CAE occurs through incremental accumulation of adverse effects, the effects caused by one project may in isolation not lead to population declines, but when combined with effects from other homo- and heterotypic sources (e.g., minerals extraction, fishing, climate change) would cause a population decline. Lastly, since population dynamics are highly complex and factors that adversely affect one species may be inconsequential to others (see

Newton 2013), the factors causing CAE will vary significantly from one species or taxonomic group to another.

Assessment of CAE of OWED on wildlife is further complicated by a lack of clarity regarding what constitutes CAE and the extent of factors (temporal, special boundaries, species to be included, etc.) to be considered in the analysis. Guidelines for CAE assessments, which aim to address questions on scoping, are broad and guidelines specific to the CAE of OWED on wildlife need to be developed.

Resolution of the challenges of CAE assessment and mitigation is both a scientific and a policy conundrum. From a science perspective, greater knowledge and data is needed about wildlife populations and how they respond to OWED. Methodological improvements also need to be made on assessment of CAE. Yet the need for improving the science is compounded by the policy issue of responsibility. Currently, in the USA the onus for a CAE assessment for a specific project falls *de facto* to the OWED project developer, who, in the process of addressing disclosure requirements, sets the stage for scientific improvements. Yet, there are limits both to the information available to a developer and to the resources the developer can put towards CAE assessment. While a developer will have detailed information about their actions, baseline population level data and information on concurrent hazards, including other projects planned or under construction, may be beyond the purview of the developer. This information gap suggests CAE assessment may be best accomplished through a two-stage process in which the developer assesses certain elements of CAE, and regional scale assessments fall to a regulating governing body.

A second science and policy issue arises in relation to the burden of mitigation. Due to CAE accumulating from a variety of both hetero- and homotypic hazards and uncertainty in effects pathways, attribution of responsibility for action is unclear. A sector-specific approach to CAE assessment of OWED on wildlife could enable the burden of mitigation to be assigned on a project-by-project basis, yet such an approach would discount heterotypic effects (e.g., fisheries bycatch). Until science progresses to the point where effects can be specifically attributed to each hazard, resolution of this issue will be, of necessity, a political determination.

Given that the offshore wind industry is still in a nascent stage, there is no immediate answer to these policy conundrums. The deployment of additional turbines will provide the opportunity to improve the understandings of wildlife response to OWED, through *in situ* studies by developers as well as regional baseline research. Nonetheless, due to the complexity of CAE, uncertainties will still remain. Thus, there is a need for more meaningful engagement on the topic of how to manage CAE in the face of uncertainty. The private–public collaborations in the UK and Europe (COWRIE, SOSS, or WE@SEA) discussed above are a start in this direction. Collaborative governance efforts could assist in developing consistent research questions, standard methodologies, and data sharing mechanisms, allowing stakeholders to iteratively inform each other of new understandings of adverse effects that accumulate to cause CAE. A notable challenge, however, is how to achieve this sharing of information while simultaneously protecting companies' proprietary information.

In sum, the development of OWED in the USA and the expansion of current capacity in the UK and Europe has significant momentum. Mitigating adverse effects that accumulate to affect populations will require clear definitions and thresholds, delegation of responsibility, careful analysis, a deliberative regulatory process, and strong private–public partnerships.

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