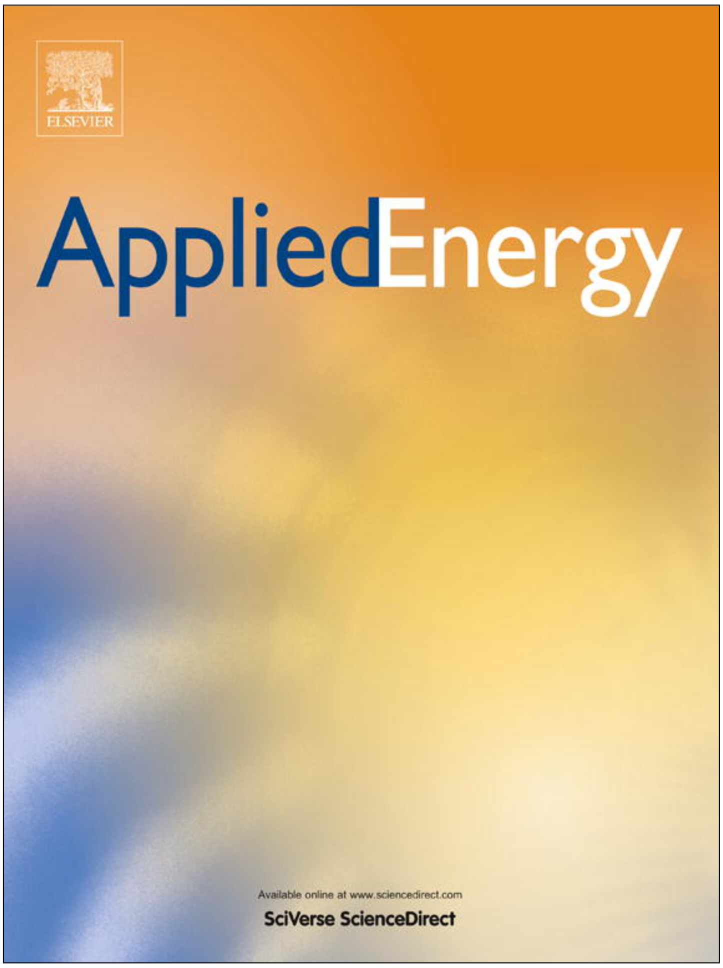

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Assessing the state of knowledge of utility-scale wind energy development and operation on non-volant terrestrial and marine wildlife

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HIGHLIGHTS

- There are many publications regarding the impacts of wind energy on bats and birds.
- In contrast, relatively little has been published regarding non-flying wildlife species.
- Wind energy can negatively affect important non-flying wildlife species.
- Impacts include mortality, habitat destruction and fragmentation, and other factors.
- More research is needed, especially before–after-control-impact studies.

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ABSTRACT

A great deal has been published in the scientific literature regarding the effects of wind energy development and operation on volant (flying) wildlife including birds and bats, although knowledge of how to mitigate negative impacts is still imperfect. We reviewed the peer-reviewed scientific literature for information on the known and potential effects of utility-scale wind energy development and operation (USWEDO) on terrestrial and marine non-volant wildlife and found that very little has been published on the topic. Following a similar review for solar energy we identified known and potential effects due to construction and eventual decommissioning of wind energy facilities. Many of the effects are similar and include direct mortality, environmental impacts of destruction and modification of habitat including impacts of roads, and offsite impacts related to construction material acquisition, processing and transportation. Known and potential effects due to operation and maintenance of facilities include habitat fragmentation and barriers to gene flow, as well as effects due to noise, vibration and shadow flicker, electromagnetic field generation, macro- and micro-climate change, predator attraction, and increased fire risk. The scarcity of before-after-control-impact studies hinders the ability to rigorously quantify the effects of USWEDO on non-volant wildlife. We conclude that more empirical data are currently needed to fully assess the impact of USWEDO on non-volant wildlife.

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1. Introduction

Renewable energy development, especially for wind and solar resources, is experiencing a renaissance in the United States and elsewhere. Although wind energy was first harnessed by humans ca. 2000 BC [1], modern wind energy development experienced its first major buildup in the mid-1970s following the Organization of Oil Exporting Countries Oil Embargo in 1973 [2,3]. Since then, demand for affordable electricity has only increased, fueling the current push to develop even more renewable energy sources. Wind energy development (Fig. 1) continues to grow rapidly worldwide, exhibiting a 15-fold increase in generating capacity from 1995 to the end of 2006, especially in Germany, Spain, India, Denmark, and the United States [4]. According to the American Wind Energy Association [5], over 35% of all generating capacity in the United States was added in the past four years, and total output for the United States now accounts for more than 20% of the world's installed wind power. From 2000 to 2009 power output from wind energy in the United States increased at an average rate of about 23% annually [6] and there is no evidence that growth is slowing. As of April 2012 over 100 separate wind energy construction projects were underway in 31 states and Puerto Rico [5]. By the year 2030, it is estimated that 72.1 km^2/TW hr/yr will be required for wind energy in the United States [7]. Based on 2009

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Fig. 1. Some areas, like this one near Palm Springs, California, were developed for wind energy in the 1980s. The effects of wind energy development and operation on non-flying wildlife species are poorly understood as reflected in a small number of peer-reviewed scientific publications on the topic. Photograph by Joshua Ennen.

license and lease data for western North America (US and Canada), [8] estimated low and high areas of shrubland ecosystem affected by wind energy development to range from 1.4 to 5.6 million ha.

Although there is wide perception that wind energy is part of a "green movement" compared to carbon-based fuel use [9], development and operation of the former does have environmental impacts [2,9,10] including impacts to wildlife. Published scientific information on the effects of renewable energy on wildlife is scant [11,12], but studies of the effects of wind energy development on birds [13] and bats [14,15] have increased due to the sensitivity of volant (flying) wildlife to aerial impacts and barotrauma, especially for bats [16]. In contrast, very little published scientific information is available on the potentially negative effects of wind energy on non-volant terrestrial and marine wildlife, although recent summaries have appeared as technical reports [17,18]. This deficiency is significant because many non-volant animals are protected as sensitive or culturally important species (e.g., game animals) that are already at risk from other forms of human development. Still others are important for their ecological roles and intrinsic value. Renewable energy development plans can usefully incorporate steps to minimize negative effects to all forms of wildlife (e.g., through the use of best management practices [17]) if those effects are known *a priori*. As others have stated, "...the green image of wind power may be jeopardized if wildlife is adversely affected." as a result of operations [19].

The objective of this paper is to assess published scientific knowledge on the known and potential effects of utility-scale wind energy development and operation (USWEDO) on non-volant wildlife (species that cannot fly), both terrestrial and marine species. As such, our review excludes consideration of ground-dwelling and ground nesting birds, although important research has been conducted on the effects of wind energy on those species (e.g., [20–22]). Our review considers both land-based and offshore [23] USWEDO. Following Lovich and Ennen [12] we focused our review on information published in peer-reviewed scientific journals for both energy and wildlife professionals, again recognizing that additional information is contained in technical reports [17,18] and the gray literature. The latter sources are beyond the scope of our review. We searched scientific journals using keywords and online search engines like Google Scholar and other subscription services for biology, the life sciences, and the energy literature available through Northern Arizona University, Cline Library. Also similar to the approach used by Lovich and Ennen [12], we divided our review into known and potential effects (both direct and indirect) of construction and decommissioning of facilities, as well as operation and maintenance of facilities. Our review provides an opportunity to identify deficiencies in the knowledge base of the effects of USWEDO on non-volant wildlife.

2. Impacts of USWEDO on non-volant wildlife

2.1. Effects due to construction and decommissioning

Construction and decommissioning of wind energy facilities involves significant ground disturbance with direct (e.g., mortality) and indirect impacts (e.g., habitat loss, degradation, or modification) on wildlife [24,11]. Wind energy projects require large areas of land estimated at 2600–6000 m^2/MW [25]. The amount of habitat loss varies with wind energy projects depending on the type and size of the installation, location, whether it is situated in degraded or undisturbed habitat, and the stage of the life cycle of the installation (e.g., construction, operation, or decommissioning) [26]. However, land area requirements vary with turbine spacing and configuration, but are typically larger than required for almost all other forms of energy production, including solar facilities of similar power output [27]. Depending on the terrain and wind availability, turbines typically occupy only 1–10% of the total wind farm but that does not include the associated infrastructure of roads, transformers, substations, and maintenance facilities included in the total footprint of the operation. Fthenakis and Kim [27] concluded that 5.5 m^2/GW h were required for wind farms with 0.5 MW turbines, while larger 1.65 MW turbines required 1.84 m^2/GW h, assuming a 30 year project lifespan.

In Europe, conservation biologists consider habitat loss from wind energy facility development a greater threat to bird populations than collision fatalities resulting from operation [11], even though the footprint of wind energy infrastructure is small compared to solar. At Danish offshore wind farms, physical disturbance related to turbine foundations usually totals more than 2–5% of the total area of the facility [28]. One typical turbine foundation affects 0.08–0.20 ha [11]. In relatively undisturbed regions, wind energy development has the potential to affect large areas of wildlife habitat.

Little information is available from the scientific literature about the direct effects of USWED on non-volant wildlife. However, as suggested by Lovich and Ennen [12], ground disturbance impacts are expected to be similar to those caused by other human activities, particularly in the desert Southwest United States [29], where wind energy has long been established [1]. This supposition is supported by modeling done by Santos et al. [30] based on data collected at wind farms in Portugal. They collected data on habitat structure (including distance to turbines) as well as the distribution of amphibians, reptiles, birds and mammals at four wind farms. Their analyses demonstrated that vertebrate species richness declined despite low wildlife mortality in the study area. They concluded that other factors including direct disturbance and structural habitat changes were responsible for the decrease in diversity.

2.1.1. Mortality of wildlife

Few published studies are available for the direct effects of USWED on the survival of non-volant wildlife. Lovich et al. [31] documented direct mortality of an Agassiz's desert tortoise (*Gopherus agassizii*, a federally and state protected species) at a wind farm in California (Fig. 2). The tortoise, an adult female with eggs, was crushed by a vehicle on a dirt road that provided access to turbines. Given the importance of reproductive females to the persistence of Agassiz's desert tortoise populations, the loss was greater than might be implied by the death of a single individual. Loss of small numbers of adult female desert tortoises can have dramatic demographic consequences on a population due to their long reproductive lifespans [32]. Indirect mortality was reported by Lovich et al. [33] for another tortoise at the same site due to entrapment in a culvert associated with facility infrastructure. Because erosion is a significant problem when wind farms are constructed in mountainous terrain [2], culverts are necessary to channel water away from infrastructure to avoid damage. In this case, an adult male tortoise used the culvert as a burrow surrogate and was entrapped when winter rains filled the culvert with sediment. Despite these human-related mortalities, the overall annual survivorship of adult female tortoises at the site was at the low end of the range reported for other tortoise populations in more natural areas. However, compared to recently low survivorship estimates for many tortoise populations (reviewed by [34]), survivorship reported by Lovich et al. [31] was relatively high.

Soil compaction can result in mortality of subterranean animals that is undetected by most survey techniques. Species that hibernate or estivate underground are especially susceptible as reviewed by Lovich and Ennen [12]. Compressive forces associated with operating heavy construction equipment at wind energy installations can collapse burrows and potentially crush small wildlife at depths of up to 60 cm.

Fig. 2. Federally protected Agassiz's desert tortoises live in a wind energy facility near Palm Springs, California. The facility was developed after 1983 and tortoises have persisted at the site since then, despite infrequent mortality events associated with site operations. Refer to text for details of studies on this population. Photograph by Jeff Lovich.

Bromley [35] suggested that hunting and poaching of wildlife was a problem associated with oil and gas exploration and development in wildlands. Similar scenarios could be envisioned at USWED sites. The author went so far as to recommend that firearms should not be allowed on the project site and in vehicles using facility access roads.

2.1.2. Destruction and modification of wildlife habitat

Construction of a wind energy facility requires alteration of some wildlife habitat for placement of infrastructure. While the loss of habitat is generally detrimental to wildlife, habitat can also be created in the form of structure, particularly at offshore wind energy facilities. These structures become artificial reefs, potentially increasing local biodiversity [26,36]. What is not understood is whether or not the benefits outweigh the cumulative negative impacts outlined elsewhere in our review. Wilson and Elliott [37] suggest that the net amount of monopile exposed per offshore turbine creates 2.5 times the amount of area lost to placement of the monopile on the sea bed.

Not all impacts of USWEDO appear to be negative for terrestrial wildlife. Lovich and Daniels [38] studied environmental attributes of burrow locations for Agassiz's desert tortoises living in a wind farm near Palm Springs, California (Fig. 2), and compared them to random points in the landscape. Data used in their study were collected about 10 years after construction of the facility commenced. The results demonstrated a statistically significant tendency for tortoise burrows to be located closer to roads and turbine structures than expected. The authors proposed two hypotheses to explain the results. First, tortoises may utilize roads to facilitate movements through their home ranges and take advantage of increased food plant resources associated with edge enhancement of vegetation (see Section 2.1.3). Second, soils at the study site lack a hardpan caliche layer, often as hard as concrete. In regions where caliche forms, tortoises often construct their burrows beneath that layer, enhancing burrow roof stability. The concrete associated with transformer pads at the site might be used as a form of artificial caliche. Tortoises at the site were frequently found in or near infrastructure associated with wind energy generation, sometimes with fatal consequences (see Section 2.1.1). However, new data collected since the study of Lovich and Daniels [38] suggest that fewer tortoises are utilizing areas in and around the wind energy infrastructure (Lovich, personal observation). It is possible that there was a delayed response by tortoises to the presence and operation of the wind farm, perhaps due to their long generation times and longevity [39]. Nest site locations in burrows of Agassiz's desert tortoises at the same wind farm were not located closer to turbines or any infrastructure associated with wind energy than burrows without nests [40]. Overall, the nesting ecology of Agassiz's desert tortoises at the site was not noticeably different from tortoises in natural areas [40].

2.1.3. Impacts of roads

Access to wind turbines for maintenance and other operational purposes requires roads [11] that have well-documented negative effects on wildlife as reviewed by Lovich and Ennen [12] for solar energy developments. Effects include direct mortality and habitat fragmentation [41–43], which can extend far beyond the physical surface of the road [44], and noise. For example, roads adversely affect species richness and abundance of some anuran species (frogs and toads) 250–1000 m beyond the actually road [45].

As mentioned above, Agassiz's desert tortoises at a wind farm in Palm Springs, California appeared to select locations for burrows in close proximity to roads, perhaps due to increased productivity of food plants [38] along the edge of the road bed [46,47]. While this relationship appears to be beneficial, it increases the chance of tortoises being killed by vehicle strikes [44], including at wind energy facilities [31]. This edge enhancement of habitat along roads actually supported similar or greater abundances of small desert mammals than sites further off the road [48]. However, with this increase of prey abundance, larger predatory wildlife could be more susceptible to vehicle strikes. In a review of the effects of roads on wildlife, Fahrig and Rytwinski [49] concluded that roads have an overall negative effect on wildlife.

2.1.4. Offsite impacts

Wind energy installations require mining large amounts of raw materials for construction including aggregate, cement, steel, and copper for wiring. This can result in direct and indirect impacts to wildlife and habitat far from the actual footprint of the installation [9]. For example, Wilburn [6] estimated the materials necessary for the United States to achieve a market goal of 20% electricity generated from land-based wind energy facilities by the year 2030. Achieving that goal would require annual production of 6.8 million metric tons of concrete, 1.5 million metric tons of steel, 310,000 metric tons of cast iron, 40,000 metric tons of copper and 380 metric tons of the rare-earth element neodymium (used in permanent generator magnets). Those amounts, with the exception of neodymium, represent less than 3% of apparent consumption of those materials in 2008. Although it is clear that there is no shortage of materials, other than possibly neodymium, large scale mining and processing will be required away from wind energy installations with concomitant impacts to wildlife and their habitat offsite. Mining for neodymium is not without risk to wildlife as shown by a spill that released radioactive waste from a rare earth element mine at Mountain Pass California [50–52] that affected habitat occupied by the federally protected Agassiz's desert tortoise.

2.2. Effects due to operation and maintenance

The adverse effects of USWED on wildlife can continue long after the construction phase of a wind energy facility is completed. These effects, which are related to the presence, operation and maintenance of turbines, are similar to effects seen in the construction and decommissioning phases. However, these effects are not ephemeral in nature and will remain over the life of the facility.

2.2.1. Habitat fragmentation

Habitat fragmentation, the process of dividing large habitat patches into smaller patches or more isolated patches, is a major concern for wildlife conservation and a key driver of species loss [53]. It can involve loss of habitat, reduced patch size, increased distance between patches, increases in new habitat through removal of existing habitat, or various combinations thereof [54]. Research demonstrates that habitat loss has large, consistently negative effects on biodiversity, but habitat fragmentation has weaker effects that are as likely to be positive as negative [55]. Differentiating the effects of loss vs. breaking connectivity of habitat requires detailed studies. Nevertheless, research demonstrates that extinction probability increases in landscapes with low or degraded native vegetative cover, low landscape connectivity, and intensive land use [53]. USWEDO has the potential to contribute to the problems associated with habitat loss and fragmentation despite the fact that a matrix of relatively undisturbed habitat can exist among turbines and other infrastructure. In fact, species that avoid vertical structures and need large unfragmented habitats are especially at risk to wind energy development [56].

Large-scale wind energy development may contribute to habitat fragmentation by presenting potential barriers to movements and genetic exchange in wildlife populations. Cryan [57] demonstrated that wind turbines impede migrations of bats so it is conceivable that other species are similarly affected by this form of habitat fragmentation. Given the near absence of specific research on the topic, it is possible that published information on the effects of oil and gas exploration and development (OGED) on wildlife in the intermountain west provides an analog for wind energy development based on density of infrastructure. We acknowledge that the comparison is largely heuristic due to operational differences between the two technologies. Previous research on OGED found numerous effects on wildlife that varied by site and species [35]. Potential impacts on large ungulates like mule deer (*Odocoileus hemionus*) and pronghorn antelope (*Antilocapra americana*) include impediments to free movement, creation of migration bottlenecks, and reduction in effective winter range size [58]. Further research demonstrated site avoidance behavior and a lack of acclimation to the disturbance by mule deer over three years of study [59,60], resulting in the use of less-preferred and presumably less-suitable habitats.

More research on the response of large ungulates to wind energy development was presented by Walter et al. [61]. They used radiotelemetry data from ten elk (*Cervus elaphus*) to measure home range size and diet before, during and after construction of a wind farm in Oklahoma. None of the elk left the site during the study and elk freely crossed gravel roads associated with the installation. Based on measurements of nutrients in feces, the authors concluded that there were no nutritional differences during construction. They concluded that, despite the loss of some grassland habitat, elk acclimate to wind energy infrastructure when construction and human presence is removed, with little impact to home ranges or nutritional ecology [61]. Research on semi-domesticated reindeer (*Rangifer tarandus*) in large field enclosures in central Norway concluded that they did not exhibit negative behavioral responses to wind turbines and turbine sounds [62] compared to controls.

Despite the absence of published data on the direct contributions of USWEDO to habitat fragmentation, Bare et al. [63] considered USWEDO to be a major impediment for gene flow without providing additional information to support their conclusion. The effects of anthropogenic habitat fragmentation on gene flow in diverse species, including both volant and non-volant taxa, have been demonstrated in southern California [64] so impacts are possible from wind energy development.

2.2.2. Noise effects

As reviewed by Lovich and Ennen [12] for solar energy development, industrial noise can have impacts on terrestrial animals including: modified habitat use and activity patterns, increased stress, decreased immune systems, reduced reproductive success, increased predation risk, degraded communication with conspecifics, and damaged hearing [65]. A significant amount of noise associated with USWED is likely to be generated during the construction and decommissioning phases [66] but significant noise can also be produced during operation and maintenance activities [67].

Wind energy facilities also produce noise during operation. Two types of noise are produced including noise from the turbine machinery inside the nacelle and noise from the blades "swishing" though the air. The latter can be noisier than the wind alone. Low frequency infrasound, below the audible range of humans, can be generated by turbulence interacting with the tower structure [9].

For USWEDO the full effects of industrial noise on wildlife are only beginning to be quantified, although research is available for both terrestrial and marine non-volant species. One of the few published studies to adequately describe the acoustic stimulus and a resulting biological response of a terrestrial animal to

USWEDO noise was that of Rabin et al. [68] for California ground squirrels (*Spermophilus beecheyi*) in a wind farm. The authors hypothesized that noise generated by wind energy turbines affected the behavior of squirrels. The species is highly social and individuals vocalize to alert other members of the colony when a predator is detected. Background noise associated with turbines could mask the ability to communicate effectively thus affecting behavior. To test their hypothesis, they compared the anti-predator behavior of two squirrel colonies: one close to turbines and another far away. Behavior was assessed during baseline conditions and during playback of squirrel alarm calls. The results demonstrated that squirrels at the turbine site showed increased caution and elevated vigilance in comparison to squirrels far away from turbines. The authors concluded that site differences were attributable to variation in noise because other factors like predator abundance, colony size, and habitat type were consistent between sites. Their experimental design met the requirements suggested for adequately assessing the impacts of noise on wildlife [65] and convincingly demonstrated a statistically significant effect [25].

Other studies on the effects of noise generated by USWEDO are available primarily for marine mammals exposed to offshore wind energy facilities [69]. Noise is of particular importance to this group of animals because many use sound for foraging, orientation (via echolocation), and communication [70]. Koschinski et al. [71] examined the behavioral response of both free-ranging harbour porpoises (*Phocoena phocoena*) and harbour seals (*Phoca vitulina*) in Canada to simulated 2 MW wind power generator noise. Behavior was also assessed under control conditions without generator noise. Both species showed a response to noise. Harbour seals surfaced at greater distances from the sound source compared to distances without noise. Similarly, approach distance to harbour porpoises increased during playback of generator noise. Echolocation detection by the porpoises increased twofold during playback of simulated turbine noise.

While these observations demonstrate behavioral responses of marine mammals to simulated wind power generator noise, three issues are worth noting. First, as of 2006, no published studies have directly measured the responses of marine mammals to noise from operating wind energy facilities [70]. Second, actual simulated noise stimuli are preferred over simulated noise for these experiments to reproduce the full frequency spectrum and temporal aspects of the noise source [65]. Koschinski et al. [71] modified original recordings of wind turbines for their experiment to compensate for cylindrical spreading of sound from the monopile foundation used on offshore wind turbines. Third, the effects Koschinski et al. [71] observed may represent best-case scenarios for the effects of sound production on wildlife because construction of offshore wind farms also involves extensive noise from seismic exploration, pile driving (capable of sound production in excess of 205 dB), helicopters, and increased ship traffic, all of which may have greater impacts on marine animals [71]. Harbour porpoises appeared to leave the construction area of one offshore wind farm after pile driving commenced [72] producing sound levels that would cause hearing loss in seals and porpoises [73]. Impact zones, perhaps extending for 80 km [72] from the impact site, depend on the low-frequency hearing abilities of the species, sound propagation conditions, and on concomitant noises as produced by shipping [70]. Based on their review of the literature, [74] concluded that there is a significant risk of negative consequences from offshore wind energy development on whales, dolphins and porpoises. Others are hopeful that implementation of mitigation strategies will minimize the negative effects and emphasize possible benefits (e.g., artificial reef creation) of USWEDO on the marine environment [36].

Results of studies from a diversity of wildlife species demonstrate that noise associated with USWEDO should be assessed for its potential to affect terrestrial and marine animals. Changes in sound level of only a few decibels have been documented to elicit substantial animal responses [65]. Ironically, sound has also been tested as an acoustic deterrent for reducing bat fatalities at wind turbines and preliminary results suggest that it may work [75]. Whether or not this technology could be used to reduce the negative impacts of wind energy on other wildlife is unknown.

2.2.3. Vibration and flicker effects

Wind energy generation produces infrasound due to turbulence associated with spinning turbines producing vibrations that can propagate for tens of km and are detectable on broadband seismometers [76]. Sounds produced by turbines are below the audible range of humans but can cause houses and other nearby structures to vibrate [9]. The effects of these vibrations on wildlife may be similar to those associated with noise as indicated above. Some animals are sensitive to frequencies below 40 Hz and are "exceptionally good" at perceiving low-frequency vibrations through their skin. Low-frequency stimuli from these sounds or vibrations are within the perceptible range of some animals that show unusual behavior before earthquakes [77,78]. Further study is clearly needed to evaluate the effects of low-frequency vibrations and sound generated by turbines on wildlife.

Wind turbines are known to produce light flicker both by interrupting sunlight (shadow flicker) and by reflection of sunlight off blades. According to [79], "The problem of shadows caused by wind turbine is not a serious issue because the turbines are relatively small and therefore did not result in long shadows." However, in mountainous terrain, large flicker shadows from operating turbines can be cast at distances of up to 1 km and are easily observable at low sun angles (Lovich, unpublished data). Flicker is of interest because rotating blades (e.g., helicopters) and other light flicker sources are known to cause seizures in humans. Analyses done by [80] suggest that flicker from wind turbines is a potential problem, even at great distances. Flicker rates of greater than 3 Hz (3/s) pose the potential to induce photosensitive seizures. To the best of our knowledge, this phenomenon has not been investigated in wildlife but given the sensitivity of many species to light [12], this is an area that requires study.

2.2.4. Electromagnetic field generation

Electric and magnetic fields are generated when electricity is passed through cables. USWEDO requires a large network of buried and overhead cables to transmit energy from turbines to the end user. Knowledge on the effects of electromagnetic fields (EMF) on humans, let alone wildlife, is controversial at present. Low-frequency EMF exposure from power lines has been associated with childhood leukemia, but no consensus among scientists has surfaced about the biological mechanisms for this association. The perceived influence of EMF exposure on wildlife varies from "small" or "minor" [36] to harmful [81,82] and contributing to some mammal species population declines [83]. For the studies citing EMF exposure as harmful to wildlife, these studies suggested that chronic exposure to athermal electromagnetic radiation could impact nervous, cardiovascular, reproductive, and immune systems [81].

Other than physiological impacts to wildlife, EMF exposure potentially could disrupt species orientation [84]. For example, [85] examined the potential effects of EMF on migratory fish species that live part of their lives in the marine environment. They found that eels of the genus *Anguilla* change swimming direction when passing over electrical cables. Whether or not this represents a biologically significant effect such as delaying migration or changing overall course remains to be determined. Nevertheless, the potential exists for species that use the earth's magnetic fields for migration to be disrupted by electrical cables. Numerous species including insects [86] to reptiles [87] use magnetic information to assist in orientation and/or migration. However, studies demonstrate that electromagnetic radiation generated by radar devices reduces bat activity significantly but not the insects on which they foraged [88]. The authors suggested that radar could be used as a possible deterrent to keep bats from approaching wind turbines. Similar to Lovich and Ennen's [12] conclusions on the impacts of EMF exposure on wildlife produced by solar facilities, the effects of USWEDO-produced EMFs on terrestrial and marine wildlife are still largely unknown.

2.2.5. Macro- and micro-climate effects

If wind energy is developed at truly large scales, modeling suggests that local and global climates could be affected by extracting kinetic energy and altering turbulent transport in the atmospheric boundary layer [89]. According to the authors, climate changes would be "nonnegligible" at continental scales even though the effect on global mean surface temperature would be minor. The authors suggested that the benefits of reduced CO_2 outputs from substitution of fossil fuels with wind power could offset the direct climatic effects.

Large wind energy facilities have the capability of changing the micro-climate in the downwind environment. Roy and Traiteur [90] and Roy [91] demonstrated that micro-climate changes occurred downwind of an operating wind farm due to enhanced vertical mixing from rotor turbulence. Basically, near-surface air temperatures can be higher at night and during early morning hours and lower during the day. They found large temperature differences during the day hours (1300–1900 h), where it was cooler downwind. These papers show that the effects of the wind farm could extend 18–23 km downwind of the facility. Local and regional effects on land surface temperatures were demonstrated at wind farms in west-central Texas by Zhou et al. [92]. The atmospheric effects of large turbines are easily demonstrated by wake clouds that form downwind of offshore facilities under certain circumstances ([93], see figure 16 therein). However, none of these studies [90–92] assessed the impact of temperature changes on wildlife. Abbasi and Abbasi [9] suggested that areas downwind of a wind energy facility may experience altered wind, precipitation and evaporation patterns, increased lake temperatures and minor changes in soil moisture. These changes have the potential to affect wildlife, especially species with environmental sex determination and narrow sex determining thresholds [94] like the federally protected Agassiz's desert tortoise, known to inhabit wind energy facilities [31,33,95].

2.2.6. Predator attraction

It is well known that wind energy facilities are associated with bird and bat mortality [11,13–15,25,96]. Carcasses are often scavenged by various species of potentially predatory animals that may be attracted to the site. Ravens (*Corvus corax*) are one predatory species attracted to areas of human activity [97], including wind energy facilities (Lovich, pers. obs.), and they are known to eat juvenile Agassiz's desert tortoises [98]. Providing raven populations with resource subsidies (including food, water, and perches for nesting associated with transmission line towers) can lead indirectly to reduction or extirpation of tortoise populations [97], especially since they are quick to learn of carcass availability [99]. Despite the potential for a "fatal attraction," we are not aware of any published peer-reviewed studies that examine the possible role of predator subsidies on wildlife mortality at wind energy facilities.

2.2.7. Fire risks

Any facility that generates electricity, including USWEDO, enhances the risk of fire. Although energy production by wind is not associated with high temperatures like concentrating solar systems, there is still a risk of fire directly related to the operation of the facility due to the presence of people and machinery. For example, several fires have been directly linked to the operation of a wind farm near Palm Springs in Southern California [95]. A recent fire was caused by a turbine malfunction that produced enough sparks to ignite the vegetation beneath the turbine, starting a fire that severely damaged native desert plant communities and habitat for the federally protected Agassiz's desert tortoise.

To our knowledge, there is no scientific literature related to the effects of fire on wildlife directly attributable to USWEDO. However, Lovich et al. [95] studied the long-term response of Agassiz's desert tortoises to fire in a wind farm near Palm Springs, California. The fire that triggered the study was started just off-site and was not attributable to wind energy operations. However, the impact of this fire is of interest, regardless of cause. Indeed, several fires have occurred at that particular site as a result of operations. Lovich et al. [95] found few differences in the activity, movements and reproductive output of the population over time, a possible result of high rainfall and plant productivity in the environment around the facility. However, in areas which are not fire-adapted, an increased fire frequency can increase wildlife mortality and alter natural plant species composition [95].

3. What are the unanswered questions and research needs?

Similar to Lovich and Ennen [12], our review of the peer-reviewed scientific literature found comparatively little information on the specific effects of USWEDO on non-volant wildlife, something noted previously by Kuvlesky et al. [11]. Direct assessment of impacts was limited to three publications on marine mammals, three regarding other marine species, one on California ground squirrels, one on small mammal populations, one on a community of mammals in Europe, one on an elk population, one on penned reindeer, and five publications on Agassiz's desert tortoise (Table 1). While it is likely that we missed other peer-reviewed publications, our preliminary assessment demonstrates that very little critically reviewed information is available on this topic. The paucity of published, peer-reviewed scientific information aids in the identification of fundamental research questions that need answers to minimize the negative effects of wind energy development on non-volant wildlife in conjunction with existing guidelines [100].

Similar to the findings of Lovich and Ennen [12] for solar energy development and operation, before-after-control-impact (BACI) studies that assess USWEDO on wildlife are rare. Besides the work of Carstensen et al. [72], we found only one other before and after study relevant to our focus on non-volant wildlife [101]. The latter authors monitored small mammal populations at a wind farm in Spain and concluded that installation of the facility had no effect despite noting that natural population fluctuations made it difficult to detect differences before, during and after construction. Other publications were *post hoc* in that data were collected <u>after</u> construction and operation of wind energy facilities. *Post hoc* analyses are valuable for finding patterns and formulating hypotheses for further research through *a priori* experimental design. According to the Kuvlesky et al. [11] only four BACI studies (two unpublished reports and two published papers on birds) were completed prior to publication of their paper (not including [72,101]).

Related to this category of research are "re-powering" projects. Some existing renewable energy facilities are now over 25 years old. For example, at our study site for Agassiz's desert tortoises in San Gorgonio Pass near Palm Springs, California the wind energy facility is powered by aging and inefficient turbines on small towers. Over 460 turbines are permitted for removal in the next few years and they will be replaced with a smaller number of large

Table 1
List of published peer-reviewed studies bearing on the effects of wind energy development, operation, maintenance, or decommissioning on wildlife. Refer to text for details of each study.

Land-based or offshore	Species	Citation (s)	Comments
Offshore	Fish and marine organisms	[26,36,37]	Underwater infrastructure may create artificial reefs that increase biodiversity
Offshore	Harbour porpoises	[72]	Harbour porpoises left the area during construction of an offshore wind farm
Offshore	Marine mammals	[70]	Review of existing literature
Offshore	Porpoises and seals	[71]	Both species showed distinct reactions to wind turbine noise
Land-based	California ground squirrels	[68]	Demonstrate increased vigilance and anti-predator behavior when exposed to wind turbine sound
Land-based	Small mammals	[101]	No effects noted despite large natural variation
Land-based	Roe deer, fallow deer, European brown hare, red fox, wild boar, badger	[105]	Essentially no differences in habitat use between areas with and without wind energy development
Land-based	Elk	[61]	Elk acclimate to wind energy infrastructure when construction and human presence is removed, with little impact to home ranges or nutritional ecology
Land-based	Reindeer	[62]	Semi-domesticated reindeer in large enclosures did not demonstrate consistently negative behavior upon exposure to turbine proximity and turbine noise compared to controls
Land-based	Agassiz's desert tortoise	[38]	Tortoise burrows appeared to be located closer to roads and anthropogenic structures than expected in a wind farm
Land-based	Agassiz's desert tortoise	[31]	Other than possible differences in growth rate of males and the high survivorship of females, long-term growth, demography and survivorship of a population in a wind farm was not appreciably different from populations in more natural areas
Land-based	Agassiz's desert tortoise	[33]	Documented mortality of an adult male in a culvert associated with wind energy infrastructure
Land-based	Agassiz's desert tortoise	[95]	Studied long-term fire ecology of tortoises living in a wind farm. Fire was not attributable to site operations
Land-based	Agassiz's desert tortoise	[40]	Nest ecology of tortoises in a wind farm was not appreciably different from populations in more natural areas

monopole turbines. Tortoises at the site appear to have acclimated to the presence of existing turbines initially [38] and 15 years of data are now available for the population [31,40,95]. Such a large-scale reoperation is equivalent to construction of a new facility in terms of ground disturbance alone. Reoperation events thus provide a valuable opportunity to examine the direct response of wildlife populations to alternative energy development when background data are available prior to construction.

Other questions asked by Lovich and Ennen [12] for solar energy that remain unanswered for wind energy include the following: (1) What are the cumulative effects of large numbers of dispersed vs. concentrated wind energy facilities on non-volant wildlife and their habitat? (2) What density or design of development maximizes energy benefits while minimizing effects on wildlife? (3) Where are the best places to site wind energy farms [102] relative to the needs of wildlife? In the case of Agassiz's desert tortoises living in a wind farm on public land near Palm Springs, California, the site was selected with little consideration of the ecological or demographic status of the local population [38]. However, by serendipity, the developers selected one of the most productive habitats for tortoise food plants in the range of the species. As a result, reproductive output is very high compared to nearby less-productive sites [103] and the tortoise population appears to be able to survive at the facility, almost 30 years after construction [31]. In this example, site selection was not a strategic decision. Leaving site selection to chance is risky at best [104]. It is important to note that we do not advocate placing renewable energy facilities in productive, high quality wildlife habitats based on this example.

4. Concluding remarks

As noted by Lovich and Ennen [12] in their review, energy is never truly "free", especially if one considers known and potential impacts on wildlife and their habitat (Table 2). Each form of energy use, including wind [27], has its own unique suite of social and environmental costs and benefits [73,102]. Minimizing environmental costs of wind energy production and maximizing benefits to society remain a laudable goal for future wind energy development. As noted by Abbasi and Abbasi [9] "*...renewable energy sources are not the panacea they are popularly perceived to be; indeed in some cases their adverse environmental impacts can be as strongly negative as the impacts of conventional energy sources.*" Based on our review of the existing peer-reviewed scientific literature it appears that insufficient evidence is available to answer the basic question, "*Is large scale wind energy development compatible with non-volant wildlife conservation?*" The issue of wildlife impacts is much more complex than considering just impacts to volant wildlife like birds and bats. Additional research is needed to fill a significant information void and more fully assess the actual and potential impacts of wind energy development on all forms of wildlife.

Table 2
List of known and potential impacts of utility-scale wind energy development, operation, maintenance and decommissioning on wildlife. Each effect is known to have impacts on wildlife even if detailed studies are not available related to wind energy. There is crossover of effects between the two columns for some impacts. Refer to the text for details.

Impacts due to facility construction and decommissioning	Impacts due to facility presence, operation and maintenance
Direct mortality	Habitat fragmentation
Destruction and modification of habitat	Noise
Impacts of roads	Vibration and flicker effects
Offsite impacts	Electromagnetic field generation
	Macro- and micro-climate change
	Predator attraction
	Fire

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References

[1] Price T, Bunn J, Probert D, Hales R. Wind-energy harnessing: global, national and local considerations. Appl Energy 1996;54:103–79.
[2] Wilshire H, Prose D. Wind energy development in California, USA. Environ Manage 1987;11:13–20.
[3] Sorensen B. A history of renewable energy technology. Energy Policy 1991;19:8–12.
[4] Golait N, Moharil RM, Kulkarni PS. Wind electric power in the world and perspectives of its development in India. Renew Sust Energy Rev 2009;13:233–47.
[5] American Wind Energy Association. Industry statistics; <http://www.awea.org/learnabout/industry_stats/index.cfm>; 2012 [accessed 10.04.12].
[6] Wilburn DR. Wind energy in the United States and materials required for the land-based wind turbine industry from 2010 through 2030. US Geological Survey Scientific Investigations Report 2011-5036; 2011. p. 22.
[7] McDonald RI, Fargione J, Kieseker J, Miller WM, Powell J. Energy sprawl or energy efficiency: climate policy impacts on natural habitat for the United States of America. PLoS ONE 2009;4:1–11.
[8] Pocewicz A, Copeland H, Kiesecker J. Potential impacts of energy development on shrublands in western North America. Nat Resour Environ Iss 2011;17:1–5.
[9] Abbasi SA, Abbasi N. The likely adverse environmental impacts of renewable energy sources. Appl Energy 2000;65:121–44.
[10] Pimentel D, Rodrigues G, Wang T, Abrams R, Goldberg K, Staecker H, et al. Renewable energy: economic and environmental issues. Bioscience 1994;44:536–47.
[11] Kuvlesky WP, Brennan Jr LA, Morrison ML, Boydston KK, Ballard BM, Bryant FC. Wind energy development and wildlife conservation: challenges and opportunities. J Wildlife Manage 2007;71:2487–98.
[12] Lovich JE, Ennen JR. Wildlife conservation and solar energy development in the Desert Southwest. US BioSci 2011;61:982–92.
[13] Drewitt AL, Langston RHW. Assessing the impacts of wind farms on birds. Ibis 2006;148:29–42.
[14] Arnett EB, Brown WK, Erickson WP, Fiedler JK, Hamilton BL, Henry TH, et al. Patterns of bat fatalities at wind energy facilities in North America. J Wildlife Manage 2007;72:61–78.
[15] Kunz TH, Arnett EB, Erickson WP, Hoar AR, Johnson GD, Larkin RP, et al. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Front Ecol Environ 2007;5:315–24.
[16] Baerwald EF, D'Amours GH, Klug BJ, Barclay RMR. Barotrauma is a significant cause of bat fatalities at wind turbines. Curr Biol 2008;18:R695–6.
[17] Mockrin MH, Gravenmier, RA. Synthesis of wind energy development and potential impacts on wildlife in the Pacific Northwest, Oregon and Washington. US Dept Agr, Forest Ser, General Technical, Report PNW-GTR-863; 2012. p. 1–55.
[18] Helldin JO, Jung J, Neumann W, Olsson M, Skarin A, Widemo F. The impacts of wind power on terrestrial mammals. Naturvardsverket, Swedish Environmental Protection Agency, Report 6510; 2012. p. 1–51.
[19] Rennian L, Xin W. Status and challenges for offshore wind energy. In: Li Y, Pan W, Ren J, editors. Renewable and sustainable energy: selected peer-reviewed papers from the 2011 international conference on energy, environment and sustainable development, October 21–23, 2011, Shanghai (China): Trans Tech Publishing; 2011. p. 601–5.
[20] Leddy KL, Higgins KF, Naugle DE. Effects of wind turbines on upland nesting birds in conservation reserve program grasslands. Wilson Bull 1999;111:100–4.
[21] Pruett CL, Patten MA, Wolfe DH. It's not easy being green: wind energy and a declining grassland bird. Bioscience 2008;59:257–62.
[22] Pruett CL, Patten MA, Wolfe DH. Avoidance behavior by prairie grouse: implications for development of energy. Conserv Biol 2009;23:1253–9.
[23] Snyder B, Kaiser MJ. A comparison of offshore wind power development in Europe and the US: patterns and drivers of development. Appl Energy 2009;86:1845–56.
[24] Harte J, Jassby A. Energy technologies and natural environments: the search for compatibility. Ann Rev Energy 1978;3:101–46.
[25] Kikuchi R. Adverse impacts of wind power generation on collision behavior of birds and anti-predator behavior of squirrels. J Nat Conserv 2008;16:44–55.
[26] Inger R, Attrill MJ, Bearhop S, Broderick AC, James WG, Hodgson DJ, et al. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. J Appl Ecol 2009;46:1145–53.
[27] Fthenakis V, Kim HC. Land use and electricity generation: a life-cycle analysis. Renew Sust Energy Rev 2009;13:1465–74.
[28] Fox AD, Desholm M, Kahlert J, Christensen TJ, Petersen IK. Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds. Ibis 2006;148:129–44.
[29] Lovich JE, Bainbridge D. Anthropogenic degradation of the southern California desert ecosystem and prospects for natural recovery and restoration. Environ Manage 1999;24:309–26.
[30] Santos M, Bastos R, Travassos P, Bessa R, Repas M, Cabral JA. Predicting the trends of vertebrate species richness as a response to wind farms installation in mountain ecosystems of northwest Portugal. Ecol Indic 2010;10:192–205.
[31] Lovich JE, Ennen JR, Madrak S, Meyer K, Loughran C, Bjurlin C, et al. Effects of wind energy production on growth, demography and survivorship of a desert tortoise (*Gopherus agassizii*) population in southern California with comparisons to natural populations. Herpetol Conserv Biol 2011;6:161–74.
[32] Doak D, Kareiva P, Klepetka B. Modeling population viability for the Desert Tortoise in the western Mojave Desert. Ecol Appl 1994;4:446–60.
[33] Lovich JE, Ennen JR, Madrak SV, Grover B. Turtles, culverts and alternative energy development: an unreported but potentially significant mortality threat to the desert tortoise (*Gopherus agassizii*). Chelonian Conserv Biol 2011;10:124–9.
[34] Esque TC, Nussear KE, Drake KK, Walde AD, Berry KH, Averill-Murray RC, et al. Effects of subsized predators, resources variability, and human population density on Desert Tortoise populations in the Mojave Desert, USA. Endangered Species Res 2010;12:167–77.
[35] Bromley M. Wildlife management implications of petroleum exploration and development in wildland environments. US Forest Service General Technical, Report INT-191; 1985.
[36] Petersen JK, Malm T. Offshore windmill farms: threats to or possibilities for the marine environment. Ambio 2006;35:75–80.
[37] Wilson JC, Elliott M. The habitat-creation potential of offshore wind farms. Wind Energy 2009;12:203–12.
[38] Lovich JE, Daniels R. Environmental characteristics of desert tortoise (*Gopherus agassizii*) burrow locations in an altered industrial landscape. Chelonian Conserv Biol 2000;3:714–21.
[39] Ernst CH, Lovich JE. Turtles of the United States and Canada. 2nd ed. Baltimore: Johns Hopkins University Press; 2009.
[40] Ennen JR, Lovich JE, Meyer K, Bjurlin C, Arundel TR. Nesting ecology of a Desert Tortoise (*Gopherus agassizii*) population at a utility-scale renewable energy facility in Southern California. Copeia 2012;2012:222–8.
[41] Forman RTT, Alexander LE. Roads and their major ecological effects. Annu Rev Ecol Syst 1998;29:207–31.
[42] Spellerberg IF. Ecological effects of roads and traffic: a literature review. Global Ecol Biogeogr Lett 1998;7:317–33.
[43] Glista DJ, DeVault TL, Woody JA. A review of mitigation measures for reducing wildlife mortality on roadways. Landscape Urban Plan 2009;91:1–7.
[44] von Seckendorff Hoff K, Marlow RW. Impacts of vehicle road traffic on desert tortoise populations with consideration of conservation of tortoise habitat in southern Nevada. Chelonian Conserv Biol 2002;4:449–56.
[45] Eigenbrod F, Hecnar SJ, Fahrig L. Quantifying the road-effect zone: threshold effects of a motorway on anuran populations in Ontario, Canada. Ecol Soc 2009;14:24. p. 18.
[46] Johnson HB, Vasek FC, Yonkers T. Productivity, diversity and stability relationships in Mojave Desert roadside vegetation. B Torrey Bot Club 1975;102:106–15.
[47] Lightfoot DC, Whitford WG. Productivity of creosotebush foliage and associated canopy arthropods along a desert roadside. Am Midland Nat 1991;125:310–22.
[48] Bissonette JA, Rosa SA. Road zone effects in small-mammal communities. Ecol Soc 2009;14:27. p. 15.
[49] Fahrig L, Rytwinski T. Effects of roads on animal abundance: an empirical review and synthesis. Ecol Soc 2009;14:21.
[50] Castor SB, Hedrick JB. Rare earth elements. In: Kogel JE, Trivedi NC, Barder JM, editors. Industrial minerals and rocks: society for mining, metallurgy and exploration; 2006. p. 769–92.
[51] Castor SB. Rare earth deposits of North America. Resour Geol 2008;58:337–47.
[52] Haxel GB, Hedrick JB, Orris GJ. Rare earth elements-critical resources for high technology. U.S. Geological Fact Sheet 087-02; 2002. p. 4.
[53] Fischer J, Lindenmayer DB. Landscape modification and habitat fragmentation: a synthesis. Global Ecol Biogeogr 2007;16:265–80.
[54] Andrén H. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. Oikos 1994;71:355–66.
[55] Fahrig L. Effects of habitat fragmentation on biodiversity. Annu Rev Ecol Evol Syst 2003;34:487–515.
[56] Kiesecker JM, Evans JS, Fargione J, Doherty K, Foresman KR, Kunz TH, et al. Win-win for wind and wildlife: a vision to facilitate sustainable development. PLoS ONE 2011;6:1–8.
[57] Cryan PM. Wind turbines as landscape impediments to the migratory connectivity of bats. Environ Law 2011;41:355–70.
[58] Sawyer H, Lindzey F, McWhirter D, Andrews K. Potential effects of oil and gas development on mule deer and pronghorn populations in western Wyoming. In: Rahm J, editor. Transactions of the sixty-seventh North American wildlife and natural resources conference, Washington, D.C; 2002. p. 350–65.
[59] Sawyer H, Nielson RM, Lindzey F, McDonald LL. Winter habitat selection of mule deer before and during development of a natural gas field. J Wildlife Manage 2006;70:396–403.
[60] Sawyer H, Kauffman MJ, Nelson RM. Influence of well pad activity on winter habitat selection patterns on mule deer. J Wildlife Manage 2009;73:1052–61.
[61] Walter WD, Leslie Jr DM, Jenks JA. Response of Rocky Mountain elk (*Cervus elaphus*) to wind-power development. Am Midland Nat 2006;156:363–75.

[62] Flydal K, Eftestøl E, Reimers E, Colman JE. Effects of wind turbines on area use and behavior of semi-domestic reindeer in enclosures. Rangifer 2004;24:55–66.

[63] Bare L, Bernhardt T, Chu T, Gomez M, Noddings C, Viljoen M. Cumulative impacts of large-scale renewable energy development in the West Mojave: effects on habitat quality, physical movement of species, and gene flow. A group project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management at the Donald Bren School of Environmental Science and Management. University of California, Santa Barbara; 2009. p. 134. <https://www.bren.ucsb.edu/research/documents/WestMojave_Final_Report.pdf>.

[64] Delaney KS, Riley SPD, Fisher RN. A rapid, strong, and convergent genetic response to urban habitat fragmentation in four divergent and widespread vertebrates. PLoS ONE 2010;5(9):e12767. http://dx.doi.org/10.1371/journal.pone.0012767.

[65] Pater LL, Grubb TG, Delaney DK. Recommendations for improved assessment of noise impacts on wildlife. J Wildlife Manage 2009;73:788–95.

[66] Suter AH. Construction noise: exposure, effects, and the potential for remediation; a review and analysis. Am Ind Hyg Assoc J 2002;63:768–89.

[67] Tougaard J, Madsen PT, Wahlberg M. Underwater noise from construction and operation of offshore wind farms. Bioacoustics 2008;17:143–6.

[68] Rabin LA, Coss RG, Owings DH. The effects of wind turbines on antipredator behavior in California ground squirrels (*Spermophilus beecheyi*). Biol Conserv 2006;131:410–20.

[69] Gill AB. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. J Appl Ecol 2005;42:605–15.

[70] Madsen PT, Wahlberg M, Tougaard J, Lucke K, Tyack P. Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Mar Ecol-Prog Ser 2006;309:279–95.

[71] Koschinski S, Culik BM, Henriksen OD, Tregenza N, Ellis G, Jansen C, et al. Behavioral reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. Mar Ecol-Prog Ser 2003;265:263–73.

[72] Carstensen J, Henriksen OD, Teilmann J. Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). Mar Ecol-Prog Ser 2006;321:295–308.

[73] Snyder B, Kaiser MJ. Ecological and economic cost-benefit analysis of offshore wind energy. Renew Energy 2009;34:1567–78.

[74] Simmonds MP, Brown VC. Is there a conflict between cetacean conservation and marine renewable-energy developments? Wildlife Res 2010;37:688–94.

[75] Arnett EB, Hein CD, Schirmacher MR, Baker M, Huso MMP, Szewczak JM. Evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines. A final report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International, Austin, Texas, USA; 2011.

[76] Styles P, Westwood RF, Toon SM, Buckingham MP-, Marmo B, Carruthers B. Monitoring and mitigation of low frequency noise from wind turbines to protect comprehensive test ban seismic monitoring stations. Fourth international meeting on wind turbine noise, Rome, Italy, 12–14 April; 2011. p. 1–13.

[77] Buskirk RE, Frohlich C, Latham GV. Unusual animal behavior before earthquakes: a review of possible sensory mechanisms. Rev Geophys 1981;19:247–70.

[78] Grant RA, Halliday T. Predicting the unpredictable; evidence of pre-seismic anticipatory behavior in the common toad. J Zool 2010;2010(281):263–71.

[79] Saidur R, Rahim NA, Islam MR, Solangi KH. Environmental impact of wind energy. Renew Sust Energy Rev 2011;15:2423–30.

[80] Harding G, Harding P, Wilkins A. Wind turbines, flicker, and photosensitive epilepsy: characterizing the flashing that may precipitate seizures and optimizing guidelines to prevent them. Epilepsia 2008;49:1095–8.

[81] Balmori A. Electromagnetic pollution from phone masts. Effects on wildlife. Pathophysiology 2009;16:191–9.

[82] Balmori A. Mobile phone mast effects on common frog (*Rana temporaria*) tadpoles: the city turned into a laboratory. Electromagn Biol Med 2010;29:31–5.

[83] Balmori A. The incidence of electromagnetic pollution on wild mammals: a new "poison" with a slow effect on nature? Environmentalist 2010;30:90–7.

[84] Irwin WP, Lohmann KJ. Magnet-induced disorientation in hatchling loggerhead sea turtles. J Exp Biol 2003;2003(206):497–501.

[85] Gill AB, Bartlett M, Thomsen F. Potential interactions between diadromous fishes of U.K. conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments. J Fish Biol 2012;81:664–95.

[86] Sharma VP, Kumar NR. Changes in honeybee behaviour and biology under the influence of cellphone radiations. Curr Sci India 2010;98:1376–8.

[87] Perry A, Bauer GB, Dizon AE. Magnetoreception and biomineralization of magnetite in amphibians and reptiles. In: Kirschvink JL, Jones DS, MacFarland BJ, editors. Magnetite biomineralization and magnetoreception in organisms: a new biomagnetism, New York (London): Plenum Press; 1985. p. 439–53.

[88] Nicholls B, Racey PA. The aversive effect of electromagnetic radiation on foraging bats – a possible means of discouraging bats from approaching wind turbines. PLoS ONE 2009;4:1–9.

[89] Keith DW, DeCarolis JF, Denkenberger DC, Lenschow DH, Malyshev SL, Pacala S, et al. The influence of large-scale wind power on global climate. Proc Natl Acad Sci USA 2004;101:16115–20.

[90] Roy SB, Traiteur JJ. Impacts of wind farms on surface air temperatures. Proc Natl Acad Sci 2010;107:17899–904.

[91] Roy SB. Simulating impacts of wind farms on local hydrometeorlogy. J Wind Eng Ind Aerod 2011;99:491–8.

[92] Zhou L, Tian Y, Roy SB, Thorncroft C, Bossar LF, Hu Y. Impacts of wind farms on land surface temperatures. Nat Clim Change 2012;2:539–43.

[93] Sun Z, Huang D, Wu G. The current state of offshore wind energy technology development. Energy 2012;41:298–312.

[94] Hulin V, Delmas V, Girondot M, Godrey MH, Guillon J-M. Temperature-dependent sex determination and global change: are some species at greater risk? Oecologia 2009;160:493–506.

[95] Lovich JE, Ennen JR, Madrak S, Loughran C, Meyer K, Arundel TR, et al. Long-term post fire effects on spatial ecology and reproductive output of female desert tortoises at a wind energy facility near Palm Springs, California. Fire Ecol 2011;7:75–87.

[96] Cryan PM. Mating behavior as a possible cause of bat mortality at wind turbines. J Wildlife Manage 2008;72:845–9.

[97] Kristan III WB, Boarman WI. Spatial patterns of risk of common raven predation on desert tortoises. Ecology 2003;84:2432–43.

[98] Boarman WI. When a native predator becomes a pest: a case study. In: Majumdar SK, Miller EW, Baker DE, Brown EK, Pratt JR, Schmalz RF, editors. Conservation and resource management. Pennsylvania Academy of Science; 1993. p. 191–206.

[99] Smallwood KS. Estimating wind turbine-caused bird mortality. J Wildlife Manage 2007;71:2781–91.

[100] U.S. Fish and Wildlife Service. U.S. Fish and Wildlife Service draft land-based wind energy guidelines: recommendations on measures to avoid, minimize, and compensate for effects to fish, wildlife, and their habitats. <http://www.fws.gov/windenergy/>; 2011 [accessed 03.03.11].

[101] De Lucas M, Janss GFE, Ferrer M. A bird and small mammal BACI and IG design studies in a wind farm in Malpica (Spain). Biodivers Conserv 2005;14:3289–303.

[102] Gamboa G, Munda G. The problem of windfarm location: a social multi-criteria evaluation framework. Energy Policy 2007;35:1564–83.

[103] Lovich JE, Medica J, Avery H, Meyer K, Bowser G, Brown A. Studies of reproductive output of the desert tortoise at Joshua Tree National Park, the Mojave National Preserve, and comparative sites. Park Sci 1999;19:22–4.

[104] Omitaomu OA, Blevins BR, Jochem WC, Mays GT, Belles R, Hadley SW, et al. Adapting a GIS-based mulicriteria decision-analysis approach for evaluating new power generating sites. Appl Energy 2012;96:296–301.

[105] Menzel C, Pohlmeyer K. Proof of habitat utilization of small game species by means of feces control with "dropping markers" in areas with wind-driven power generators. Z Jagdwiss 1999;45:223–9.