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Wind, sun, and wildlife: do wind and solar energy development 'short-circuit' conservation in the western United States?

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Abstract

Despite the trade-offs between renewable energy development, land use, humans, and wildlife, wind and solar development continues to transform the western US into a green energy landscape. While renewable energy reduces carbon emissions and reliance on fossil fuels, many studies have emerged on the associated ecological and social impacts of this technology. Here, we review the current state of knowledge on the nexus between wildlife conservation and energy development in the western US since 2010. We revisit pertinent ecological concepts presented in earlier reviews to assess how far the field has progressed in mitigating negative effects. Specifically, we examine: (*i*) recent trends in the literature on how wind and solar energy development impact wildlife in the US, (*ii*) how siting and design of development may maximize energy benefits while minimizing negative effects on wildlife, (*iii*) the availability and benefits of before-after control-impact studies, and ultimately (*iv*) how impacts of renewable energy development on wildlife may be mitigated. We also provide case studies on the desert tortoise and greater sage-grouse, two conservation-reliant umbrella species in the western US, to highlight efforts to mitigate the effects of solar and wind energy development, respectively. We recognize that many other species are affected by renewable energy development, but desert tortoises and sage-grouse are representative of the conflicts that need to be addressed. Our review concludes that mitigation can be improved via use of spatial decision support tools, applying novel wildlife deterrence and detection systems developed for existing installed facilities, and incorporating impact studies that provide managers with conservation metrics for evaluating different future development land-use scenarios.

1. Introduction

The southwestern US has the largest solar energy potential in the country (Lovich and Ennen 2011, Kabir *et al* 2018), and wind energy has been providing power there since the 1980s (Pasqualetti 2001). Renewable energy development potential in the region is leveraged by the availability of massive areas of undeveloped land—much of it owned and managed by the government for public or military purposes, including renewable energy development. In response, California, the most populous state in the region, has adopted an aggressive renewable energy portfolio that will require 60% of electricity to be sourced from renewable energy by 2030 and 100% by 2045 (Renewables Committee 2018). These bold energy efficiency targets accompanied by a growing positive perception of renewable energy technologies by the public are driving a rapid expansion of renewable energy development in the western US (Hamilton *et al* 2018). For example, US renewable electricity generation has nearly doubled since 2008—presently 742 million megawatt hours—with a predicted rise of ~68% by 2040 (Trainor *et al* 2016, Annual Energy Outlook 2020 with projections to 2050, available online at www.eia.gov/aeo). Prioritization of energy efficiency and renewable resources supports ongoing global efforts to reduce global carbon emissions, lessen reliance on fossil fuels, and mitigate climate change (Edenhofer *et al* 2012, Quaschning 2019). However, trade-offs between energy production, land availability, human dimensions (Steg *et al* 2015), and conservation priorities—including wildlife responses to habitat modification in renewable energy hotspots (e.g. Vandergast *et al* 2013, Wood *et al* 2013)—create conflicts (Mulvaney *et al* 2017) and may limit the demand for renewables (Gibson *et al* 2017).

Renewable energy development involves deployment of extensive infrastructure on public and private land (Hernandez *et al* 2015a), including previously undisturbed land with sensitive wildlife species (e.g. Lovich *et al* 2011). However, human and environmental constraints limit the locations where these renewable energy developments are compatible. Additionally, design and development criteria that maximize energy potential do not necessarily incorporate steps for minimizing negative effects on all resident wildlife (Thomas *et al* 2018). To address these issues, previous researchers have quantified the capacity-based technical potential and identified accessible energy potential that exist in the currently-built environment (Hernandez *et al* 2014). Other studies have noted that reducing environmental impacts, especially to sensitive fauna, also relies on comprehensive before-after-control-impact (BACI) studies that provide critical information on the direct responses of sensitive wildlife (Lovich and Ennen 2011, 2013). Nonetheless, whether these suggestions have been effectively integrated with recent renewable energy development in the desert Southwest remains to be reviewed.

Development, operation, and maintenance of renewable energy facilities have known and potential impacts on wildlife, including habitat fragmentation, barriers to gene flow, as well as effects due to noise, vibration, macro- and micro-climate change, predator attraction, and increased fire risk, as reviewed by Lovich and Ennen (2011, 2013). Besides the direct loss of habitat and associated mortality of wildlife during the construction phase, the operation of renewable energy facilities can also cause direct mortality of wildlife. Exposure to wind energy operations may cause putative negative effects to humans living nearby as well. Tinnitus, ear pain, and vertigo have been reported following exposure to wind facility noise pollution (Farboud *et al* 2013). Even epileptic seizures are possible from exposure to the light or shadow flicker created by rotating turbine blades (Harding *et al* 2008). However, much of the literature associated with human-health effects provide inconclusive evidence (Schmidt and Klokker 2014), and some argue that there are no 'direct causal link' between human-health and wind turbines (Knopper and Ollson 2011), with the exception of increased sleep disturbance (Knopper *et al* 2014).

Bird and bat mortalities associated with aerial impacts and barotrauma in wind energy facilities are frequently reported in the literature (e.g. Drewitt and Langston 2006, Arnett *et al* 2011) although the accuracy of estimates of the actual numbers killed is uncertain for several reasons, especially data deficiencies that vary from region to region (Allison *et al* 2019). Additional research documents direct mortalities associated with solar energy operation, that include burns, vaporization, and collisions of birds and insects with infrastructure (McCrary *et al* 1986, Manville 2016, Horváth *et al* 2010, Walston *et al* 2016, Visser *et al* 2019). Nearly half of all bird collisions in utility-scale wind facilities in the US occur in California (Gibson *et al* 2017). Additionally, an estimated 16 000–59 000 birds are killed each year by utility-scale solar energy development in the southern California region (Walston *et al* 2016). Bird and bat fatality rates vary substantially from region to region with as many as 600 000 birds per year and 800 000 bats per year killed in the continental US from 2013–2014 (Allison *et al* 2019). For some species of birds, wind farm construction has greater impacts on populations than post-construction operations (Pearce-Higgins *et al* 2012). For terrestrial species, noise produced by wind turbines is shown to modify behavior (i.e. increased vigilance and caution; Rabin *et al* 2006), leading to avoidance of the interiors of wind facilities (Łopucki *et al* 2017). In addition, wind energy facilities can also induce physiological responses (i.e. increased corticosterone) in nonvolant mammal species (Łopucki *et al* 2018).

While many impact studies focus on population-level responses in wildlife, recent studies suggest that plant and animal communities exhibit lower diversity, richness, and evenness within the boundaries of renewable energy facilities (Santos *et al* 2010, Keehn and Feldman 2018, Visser *et al* 2019). Communities within renewable energy facilities have fewer rare species and more non-native plant species (Keehn and Feldman 2018). Furthermore, there is recognition that wind farms can have cascading effects on ecosystems due to mortality of predatory species (Thaker *et al* 2018).

Other impacts related to renewable energy could occur due to local and regional effects on climate that affect wildlife and their habitats. For example, micro- and macro-climate changes are well documented for wind energy facilities (Roy and Traiteur 2010, Roy 2011, Walsh-Thomas *et al* 2012, Cervarich *et al* 2013, Rajweski *et al* 2014, Miller and Keith 2018, Moravec *et al* 2018), but are less well-known for solar (Millstein and Menon 2011, Zhou *et al* 2012, Suuronen *et al* 2017). Most studies suggest that the operation of these renewable energy facilities could cause local warming and even affect weather patterns at a broader scale. However, there is a dearth of literature focusing on the wildlife-related impacts from these micro- and macroclimate changes, especially for ectotherms and species with temperature-dependent sex determination (Lovich and Ennen 2011, 2013). Nonetheless, Armstrong *et al* (2014) suggest that renewable energy facilities have the potential to alter plant-soil carbon cycling through ground-level microclimate alterations, disrupting a major atmospheric sink for CO_2 (Evans *et al* 2014). Some micro-climate effects could be beneficial to humans. Colocation of solar energy development in agricultural environments can reduce drought stress and increase food production in several crops (i.e. chiltepin pepper, jalapeño, and cherry tomatoes) through the effect of shading by solar panels (Barron-Gafford *et al* 2019).

A central challenge at the intersection of conservation prioritization and renewable energy development revolves around understanding, managing, and mitigating environmental problems, while concomitantly sustaining development and meeting energy efficiency targets (Katzner *et al* 2013). Although several studies have reviewed and alerted resource managers to environmental impacts and potential mitigation strategies (Lovich and Ennen 2011, 2013, Northrup and Wittemyer 2013, Hernandez *et al* 2014, 2015b, Moore-O'Leary *et al* 2017), an ongoing discussion of how these suggestions have affected or assisted recent development in the western US is pivotal to minimizing negative impacts to wildlife in the future (Bachelet *et al* 2016). Thus, the overall objective in this paper is to review the current state of knowledge on the nexus between wildlife conservation and wind and solar energy development, focusing on the western US. Specifically, we review recent literature to see if the questions and research needs posed in earlier reviews (Lovich and Ennen 2011, 2013) have been addressed and translated into effective management for mitigating known and potential negative effects. Specifically, we examine: (*i*) recent trends in the literature on how wind and solar energy development impact wildlife in the US; (*ii*) how siting and design of development may maximize energy benefits while minimizing negative effects on wildlife; (*iii*) the availability of BACI studies; and ultimately (*iv*) how impacts of renewable energy development on wildlife may be mitigated. We provide case studies of the desert tortoise (*Gopherus agassizii*) and greater sage-grouse (*Centrocercus urophasianus*) as examples of conservation-reliant, umbrella species that highlight efforts to mitigate the effects of existing and ongoing renewable energy development in the US.

2. Methods

We searched the Thomson Reuters Web of Science™ Core Collection and Google Scholar for journal articles that assessed the interaction between wildlife and renewable energy in the US since our earlier state-of-knowledge reviews were published (Lovich and Ennen 2011, 2013). We conducted the search in May 2019 with a time range of 2010–2018, using the search terms (renewable energy development*United States*wildlife, and wildlife*solar energy OR wind energy). We recognized that these terms are not all encompassing of the extensive renewable energy literature; however, they would capture most of the literature pertaining to the renewable energy-wildlife conflict in the Western US—the focus of our review. Moreover, as our search was limited to titles, topics, and keywords, our review was not exhaustive, but likely represents articles in which renewable energy wildlife assessments, impacts, and mitigation were a key component. We included global studies that provided data or insight on renewable energy in the US. We also supplemented our literature search using the National Renewable Energy Laboratory Wind-Wildlife Impacts Literature Database and selecting search terms: North America, Journal Article, and publication years 2010–2018. We excluded studies that did not occur in North America (although we discuss some studies outside the region as appropriate to our review), and/or did not mention wildlife. We classified and/or characterized these studies according to broad category classes including energy type (Wind, Offshore Wind, Solar, or Multiple), wildlife species group (Volant, Terrestrial, Aquatic, Marine, or Other if the article did not mention a specific taxa), approach (Empirical, Review, Policy Piece, Perspective), topic (Ecological, Conservation Planning, Social), and state or province (Continental US or Canada). Finally, we chose to review peer-reviewed scientific literature only and exclude all grey literature as was done in previous reviews of renewable energy development on wildlife (Lovich and Ennen 2011, 2013). While such exclusion may limit our understanding of actual renewable energy development design plans and impacts, grey literature does not go through anonymous peer review and thus is not equal to scientific publications. In addition, grey literature can be hard to find and may not be readily available to readers to substantiate citations. While our review may not actually reflect the complete state of knowledge, it does provide a reference point or baseline for published scientific synthesis.

Using empirical studies only, we classified the 'impact concept' that the authors evaluated in the journal article. Impact concepts included: (*i*) siting (i.e. proximity of facilities relative to wildlife migratory paths, critical resources or habitats, and regional topography and climate), (*ii*) design (i.e. placement of infrastructure within facility, infrastructure lights, spatial density of infrastructure, height, size, angle, speed, reflectance, sound and vibration projection, habitat fragmentation, and maintaining critical habitats within and adjacent to facilities), (*iii*) operation (i.e. facility maintenance, turbine intermittency, and malfunctions including fires), and (*iv*) development (i.e. construction activities, habitat destruction and loss, and permanent or temporary translocation). Using a Pearson's pairwise correlation matrix, we evaluated the relationship between yearly total publication counts for each of the impact concepts (siting, design, operation, and development) and energy type (wind, solar, and offshore), taxonomic group focus (volant, terrestrial, and marine), and year. All analyses were produced using Program R 2018 and a significance level of $p < 0.05$.

3. Results and discussion

3.1. Literature trends

Our search returned 232 journal articles concerning renewable energy (wind and solar) and wildlife in North America from 2010–2018 (table 1). The number of journal articles published each year varied over time from nine in 2010 to 24 in 2018 and peaked in 2013 with 39 publications. Journal articles were predominantly empirical research studies (68%) and focused on the effects of wind energy (72%) with an ecological focus (57%) and volant species assessment (54%) (table 1, figure 1). The least studied subcategory included the species group aquatic taxa (1%) (table 1). These results are similar to the findings produced in previous reviews, such that relatively little has been published regarding non-volant wildlife species (Lovich and Ennen 2011, 2013). Nonetheless, our results show an increased focus on environmental impacts resulting from renewable energy development over the past decade, as a previous review conducted in 2005 noted that only 4% of all publications on the topic covered ecological impacts (Gill 2005). Evaluating empirical studies only from 2010–2018, the total number (i.e. count) of studies that focused on renewable energy development increased with year, the total number of studies that focused on renewable energy design was positively correlated with the total number of studies focused on volant species, wind and offshore wind technology; and the total number of studies that focused on renewable energy siting was positively correlated with topics including wind energy technology (figure 2). The geographic distribution of studies produced in our review reflects a strong focus on the western US. As such, wildlife impacts in California were a primary target for 17% of the research studies reviewed, followed by Texas (5.5%) and Wyoming (4%). These results may reflect the accelerated growth and potential of renewable energy development in the American West, and that most of the installed or planned utility-scale facilities are located in states such as California, Arizona, and Texas.

3.2. Site selection and design

Our literature review revealed that 13% of journal articles mentioned or focused on the importance of renewable energy siting or facility design. This figure is surprisingly low. As pointed out by Arnett and May (2016) in their review of how to mitigate the effects of wind energy on various animals, avoidance of predicted high risk areas is the logical first step of effective mitigation. The same tenet applies to solar energy development. Selecting the optimal location for the footprint of the facility is paramount for minimizing negative impacts on sensitive species and habitats. Examples of sensitive areas for wildlife include: core habitats (e.g. winter or summer range for ungulate populations like Mule Deer (*Odocoileus hemionus*), Webb *et al* 2013); lekking areas for Prairie Chickens (*Tympanuchus cupido*) (Smith *et al* 2016); riparian areas, especially in the arid western US (Grippo *et al* 2015); and along migratory corridors (e.g. Johnston *et al* 2014).

Alternative locations that have little or no impact on wildlife include built or already disturbed environments, as exemplified by roof-top solar in urban areas, that confer environmental co-benefits including conserving wildlands (Moore-O'Leary *et al* 2017, Assouline *et al* 2017), and recommendations to direct future development of wind energy toward already disturbed lands in the US (Kiesecker *et al* 2011). However, large-scale deployment at these locations may have wider reaching implications that affect wildlife and their habitat (Millstein and Menon Millstein and Menon 2011) far beyond. Other locations with substantially reduced or eliminated negative effects on wildlife include brownfields, like contaminated industrial sites (Adelaja *et al* 2010, Stoms *et al* 2013) and agricultural areas (e.g. Barron-Gafford *et al* 2019). Redevelopment of such sites for energy production can result in substantial economic benefits to local communities as well. Grassy areas around airports can also be used for solar energy development (Devault *et al* 2012) as one of the few areas where reductions in wildlife abundance and habitat quality are necessary and socially acceptable, to reduce wildlife collisions with aircraft. Since 2010, there has been little evidence of a reduced emphasis on the development of utility-scale solar energy in wildlands (particularly shrublands) of the southwestern US, as illustrated by the situation in California (Hernandez *et al* 2015a). Parker *et al* (2018) found that solar development in the Mojave Desert as of about 2010 had a footprint of 86.79 km^2: 25.81 km^2 (29.7%) of this was primarily high conservation value public lands in Ivanpah Valley, and 60.99 km^2 (70.3%) was privately owned lands, mostly of lower conservation value, in the western portion of the Mojave Desert.

As reviewed by Arnett and May (2016), a number of tools are available to the renewable energy sector to make informed decisions on renewable energy site selection, including minimizing or eliminating negative impacts to wildlife. Included are detailed maps maintained by state resource management agencies and conservation organizations showing the distribution of sensitive wildlife and their habitats. Another option is to use various models of species occurrence and diversity as was done by Thomas *et al* (2018) for wind and solar energy in Arizona, USA. The premise in this analysis is that areas that have high biodiversity or concentrations

Table 1. Literature review results from 232 publications, including total number of publications by energy type, wildlife species group, approach, topic, and location (i.e. US State provided if specified in publication, therefore the total number does not add to 232 in Location column). Subcategories ordered from highest to lowest number of publications.

Location	Species Group	Approach	Energy Type	Topical Area
CA (41)	Volant (128)	Empirical (158)	Wind (152)	Ecological (131)
TX (13)	Other (44)	Review (60)	Multiple (42)	Other (101)
WY (11)	Multiple (24)	Policy Piece (12)	Solar (21)	
KS (6)	Terrestrial (22)	Perspective (2)	Offshore Wind (17)	
MD, ND, SD, CO, WI, AZ, RI, PA, WA, NE, IA, OH, OK, OR, NY (2–5)	Marine (13)			
ID, IL, IN, MA, MO, NV, NJ (1)	Aquatic (1)			

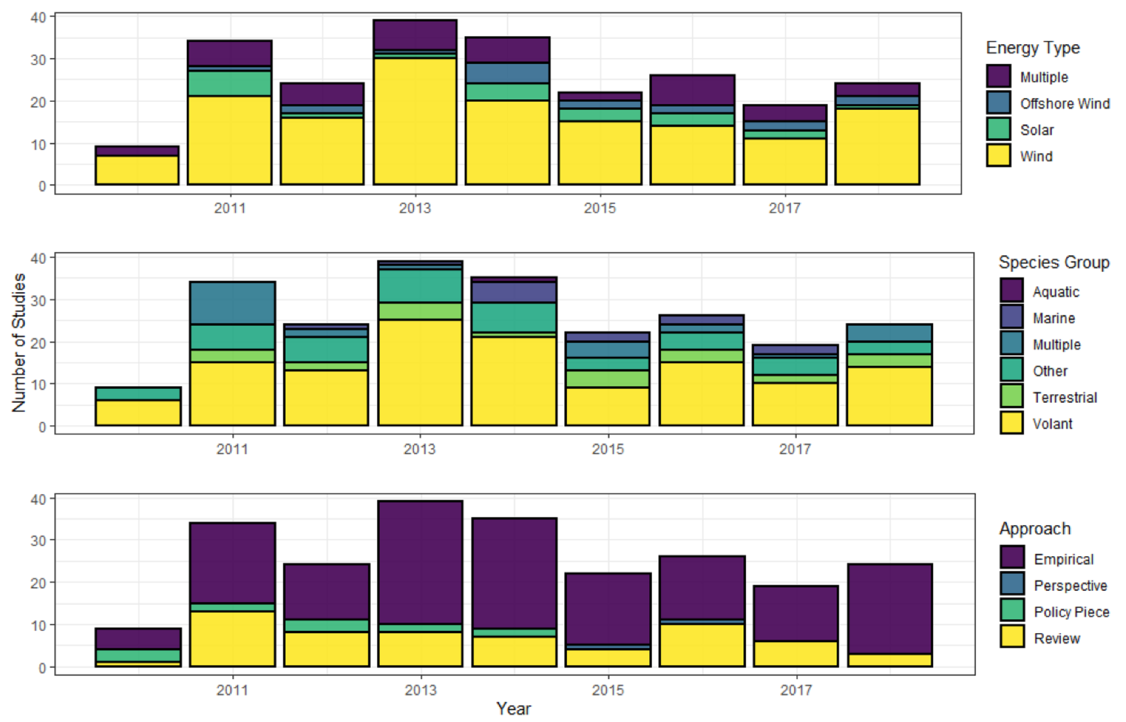

Figure 1. The total number or count of renewable energy publications over time from 2010 to 2018 in the United States, parsed by energy type, taxonomic group, and approach.

of sensitive species should be avoided. The availability of publicly accessible vertebrate habitat models for the entire US adds to the value of this technique. Others have examined the occurrence of high genetic diversity and connectivity in the western US (Vandergast *et al* 2013, Wood *et al* 2013) to identify areas of high conservation value relative to siting solar projects.

In contrast to what most authors conclude about site selection, other studies suggest that '…*responsibly developed solar power plants can provide shelter, protection, and stable use of land to support biodiversity*' (Sinha *et al* 2018), using the Topaz Solar Farms Project in southern California as an example. During post-construction surveys, the authors documented similar or increased vegetative productivity compared to reference sites. They also documented continued occupancy of sensitive wildlife species. One of those species is the federally-endangered San Joaquin Kit Fox (*Vulpes macrotis mutica*). By working with biologists, project managers developed and installed a fence that allowed passage of Kit Foxes but prevented adult Coyotes (*Canis latrans*), a predator of the former, from entering the facility, thus providing a level of protection to Kit Foxes (Cyper B 2019 *Personal Communication*).

3.3. BACI studies

BACI designed studies are considered to be the 'optimal impact study design' (Green and Green 1979), and the preferred method to determine displacement of wildlife by energy development (Strickland *et al* 2011). Despite the known benefits of the BACI design (i.e. strong management inferences, mitigation strategies for future development), these types

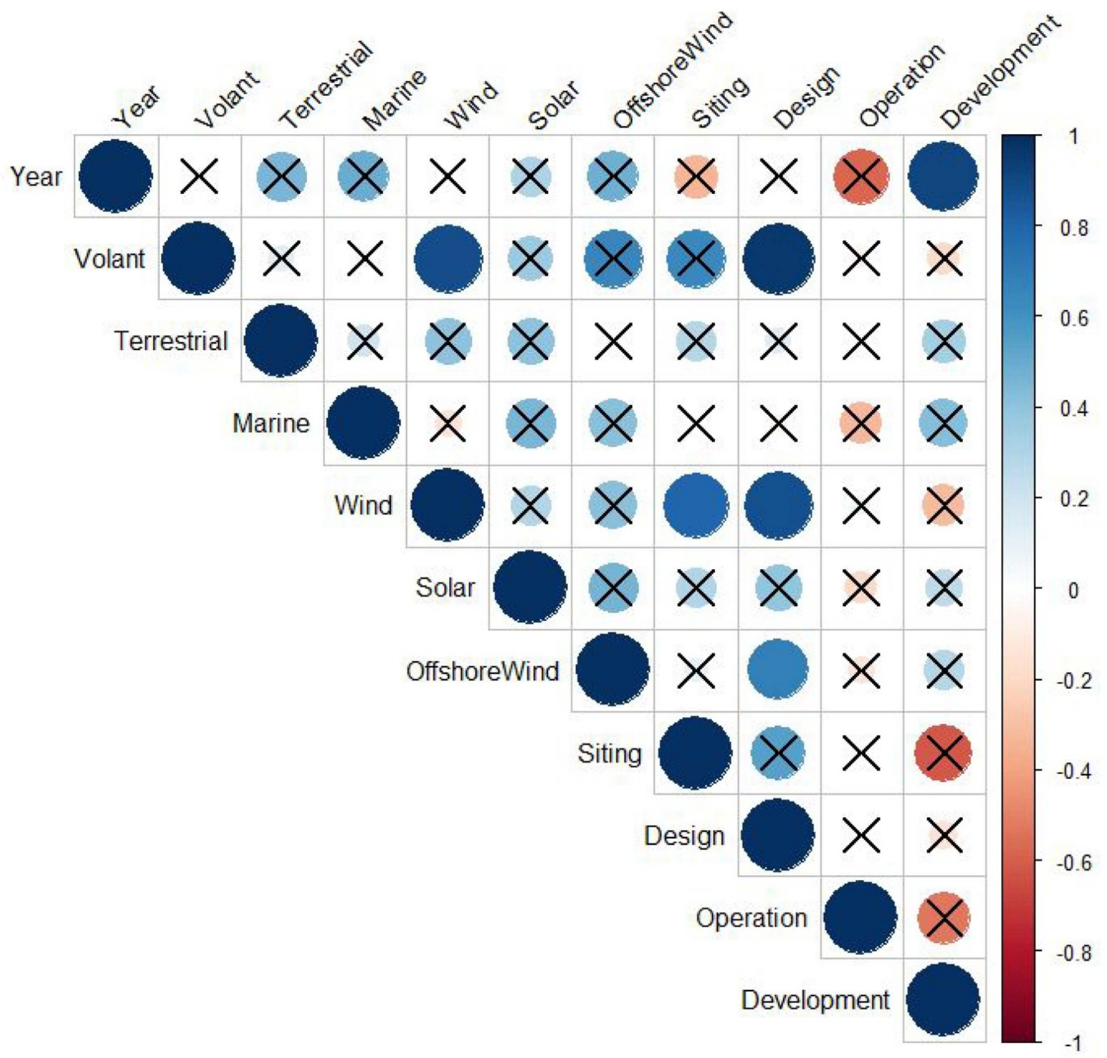

Figure 2. A correlation matrix of study counts where correlation coefficients are colored according to value and insignificant correlations (P > 0.05) are crossed out. Study counts are parsed by year, taxonomic group (volant, terrestrial, marine), renewable energy type (wind, solar, and offshore wind), and impact focus (siting, design, operation, and development).

of studies are difficult to conduct as they require prior knowledge of site selection by developers and long-term data and funding to match timing of development. Unsurprisingly, BACI studies that evaluate impacts on wildlife remain rare, similar to the findings of Lovich and Ennen (2011, 2013) for renewable energy development and operation nearly ten years prior to our study.

Our present review identified only five studies (2%) that mention BACI as a necessary analysis for understanding the relative effects of renewable energy development on wildlife. Of those five studies, three studies conducted a BACI analysis in the US (Mcnew *et al* 2014, Shaffer and Buhl 2016, Lebeau *et al* 2017). These investigations performed a BACI assessment to determine whether wind facilities placed in prime wildlife habitat affect survival of displaced bird species and their associated nesting habitats. Use of BACI in these research efforts provided potential avenues for mitigating impact of energy development (Mcnew *et al* 2014), and metrics to facilitate future development models for evaluating impacts of renewable energy facilities under differing land-use scenarios. While BACI-design studies are difficult to conduct, they remain an important approach for understanding how we can mitigate environmental impacts and improve site selection and design of future utility-scale renewable energy developments. Without more BACI studies, our knowledge is severely restricted in understanding the true impacts of these facilities on wildlife.

3.4. Mitigation

The mitigation hierarchy is avoidance, minimization, and compensation (Arnett and May 2016), or restoration (Kiesecker *et al* 2010). However, there is no 'silver bullet' solution along the mitigation pathway to protect all species from impacts of renewable energy facility development and operation, except total avoidance. In short, all energy sources will come with a cost to some wildlife, and each particular mitigation technique and strategy is usually species-biased, site-specific (Moore-O'Leary *et al* 2017), and will not cover the entire wildlife community being affected.

The best mitigation strategy is to avoid developing sensitive and pristine areas, which can be assessed in the pre-construction phase to identify issues related to wildlife, especially sensitive and threatened species (Arnett and May 2016; see above). Most of the known mitigation literature—in particular, solar energy-related literature—focuses on spatial planning and avoiding sensitive areas (Cameron *et al* 2012, Stoms *et al* 2013, Hernandez *et al* 2015a, 2015b, Kreitler *et al* 2015, Arnett and May 2016; see above), and less so on minimization or compensation strategies.

However, there has been progress in minimizing impacts from existing renewable energy facilities, especially wind energy, but not necessarily for solar energy. For example, studies have reported positive results—reduced mortality—for repowering wind turbines (Smallwood and Karas 2009), using automated monitoring (Mcclure *et al* 2018), sensors (Hu *et al* 2018) and acoustic deterrents (Arnett *et al* 2013), and adjusting operation times (Singh *et al* 2015) and cut-in speeds (Barrios and Rodriguez 2004, Smallwood *et al* 2009, Arnett *et al* 2011). However, for many of these mitigation strategies, there are published studies with conflicting results, suggesting that success is highly variable and site-specific (Arnett and May 2016). Thus, use of BACI studies may improve our understanding of how these mitigation strategies could be improved and how alternative facility designs may continue to evolve.

Finally, offsite compensatory mitigation is a 'last resort' strategy that includes land acquisition, preservation, and restoration of offsite habitats (Hartmann and White 2019). These actions are rare for wind and solar energy developments (Arnett and May 2016, Hartsmann and White 2019), but were, at one point, required under various federal laws (e.g. Clean Water Act and Endangered Species Act [ESA]; Hartmann and White 2019). However, the federal requirement of compensatory mitigation was rescinded in March 2017 by an Executive Order and federal agencies need not require compensatory mitigation for project approval (Hartmann and White 2019). Now, compensatory mitigation as a requirement for project approvals falls within state jurisdiction (Hartmann and White 2019).

3.5. Case studies: desert tortoises and greater sage-grouse in the American West

As previously noted, the desert Southwest US is a hotspot for renewable energy development (Bachelet *et al* 2016). Despite its appearance as a rugged and timeless landscape, this arid region is sensitive to disturbance and recovers very slowly from anthropogenic disturbances (Lovich and Bainbridge 1999), including renewable energy development (Hernandez *et al* 2014, 2015a). It is also home to a surprisingly diverse group of animals that are affected by both solar and wind energy development and operation (Lovich and Ennen 2011, 2013). Included are federally protected, conservation-reliant species like the two species of desert tortoises (*Gopherus agassizii* and *G. morafkai*) and greater sage-grouse (*Centrocercus urophasianus*), all of which are threatened by renewable energy development.

Greater sage-grouse and desert tortoises receive a great deal of state- and federal-level conservation attention due to their declines and sensitivity to habitat loss. Both taxa are considered indicator or umbrella species due to their interaction with a myriad of species including other federally listed species, and are sensitive to changes in the environment (Grodsky *et al* 2017, Lebeau *et al* 2017a, Pilliod *et al* 2020). As an ecosystem engineer, Agassiz's desert tortoises provide habitat for many animals that cohabitate burrows like rodents, snakes, lizards, mesocarnivores, and ground birds including burrowing owls (*Athene cunicularia*) (Agha *et al* 2017); it also shares similar habitat to that of the federally threatened Mohave ground squirrel (*Xerospermophilus mohavensis*) (Logan 2016). As a wide-ranging sagebrush prairie-grassland species, greater sage-grouse co-occur with a host of other similar volant species that occupy the same habitat in the western US, including the golden eagle (*Centrocercus urophasianus*)—a species also considered to be ecologically important and affected by renewable energy development (Lovich 2015, Tack *et al* 2020).

Solar energy development in desert tortoise habitat is a significant concern for recovery of the species (Lovich and Ennen 2011). Prior to the listing of the desert tortoise under the ESA in 1990, renewable energy development was a minor contributor to habitat destruction of tortoises around the time of listing (Baxter and Stewart 1986, Pasqualetti 2001).With the recent buildout of utility-scale solar and wind facilities in the region, there is now concern that renewable energy development poses a substantial risk to tortoise populations, primarily through habitat destruction, fragmentation, and modification (Lovich and Ennen 2011, Averill-Murray *et al* 2012, Lovich *et al* 2018). To date, mitigation of solar energy development in tortoise habitat has relied almost exclusively on mitigation translocation (as opposed to conservation translocation, see Sullivan *et al* 2015) and/or head-starting. Although these sound like simple and logical solutions, these strategies have been criticized for various reasons, especially the fact that it has a low success rate for many reptiles and amphibians (Frazer 1992, Seigel and Dodd 2000, Germano and Bishop 2008, Sullivan *et al* 2015), including desert tortoises (Mack *et al* 2018). Nevertheless, the promise of success has led to renewed interest in both strategies for desert tortoises (Sadoit *et al* 2017, Dickson *et al* 2019, Tuberville *et al* 2019). Over five years post-translocation, desert tortoises displayed no adverse effects on condition, growth, or mortality (Sadoti *et al* 2017, Dickson *et al* 2019). Several noticeable short-term effects related to translocation include restricted movements caused by barrier fences (Sadoti *et al* 2017, Peaden *et al* 2017), higher average maximum daily shell temperatures (Brand *et al* 2016), larger home ranges (Fransworth *et al* 2015), and males siring fewer offspring (Mulder *et al* 2017).

Head-starting is another potential mitigation strategy for energy development in tortoise habitat (Tuberville *et al* 2019). This involves raising juvenile tortoises in captivity until they attain a size making them less susceptible to mortality from predation and other factors. Again, there is controversy in the scientific literature about the effectiveness and value of head-starting (Frazer 1992), including for desert tortoises (Mack *et al* 2018), but the promise of success has led to renewed interest in head-starting desert tortoises. Research is ongoing regarding how to enhance the success of juvenile tortoises after head-starting (Hazard and Morafka 2002, Hazard *et al* 2015, Nagy *et al* 2015a, 2015b, 2016, Daly *et al* 2018, Tuberville *et al* 2019). Notwithstanding the promising results suggested by short-term studies of translocation and head-starting of desert tortoises as mitigation strategies for renewable energy development, long-term data are yet unavailable for this long-lived species to conclude ultimate success.

Thus far, concerns about the negative effects of wind energy in the western US have focused mostly on mortality and habitat displacement for birds and bats (see recent review in Allison *et al* 2019), although some information is available for non-volant species (Lovich and Ennen 2013, Agha *et al* 2015, 2017). For instance, impacts of wind energy development and operation on desert tortoises increases mortality associated with road infrastructure (Lovich and Ennen 2011), facility infrastructure fire effects on habitat (Lovich *et al* 2018), and displacement over the long-term (Lovich and Ennen 2017).

Similar to desert tortoises, greater sage-grouse are threatened by a variety of anthropogenic- and ecosystem-based factors including natural resource extraction, land conversion for agriculture and development, invasive plant species, wildfires, and most recently wind energy development (Chambers *et al* 2017). Some studies have noted a negative effect of energy development on their survival, such that increased surface disturbance, noise, and habitat fragmentation can lead to lower nest and brood survival (Lebeau *et al* 2014, Kirol *et al* 2020). For instance, continuous monitoring of 95 nests and 31 broods at an operating wind energy facility in Wyoming, USA revealed that risk of nest and brood failure increased within habitats of proximity to wind turbines (Lebeau *et al* 2014). Additionally, LeBeau suggested that it is critical to identify nesting and brood-rearing habitat when evaluating potential impacts of wind energy development on overall population fitness (Lebeau *et al* 2014). Although the knowledge on impacts of wind energy on the greater sage-grouse is limited, there is plenty of information about the impacts of infrastructure associated with oil and gas developments that can guide managers (Kirol *et al* 2015, 2020). For example, yearlings exhibit avoidance behavior near energy infrastructure, lower survival reared within energy infrastructure, and less frequently establish breeding territories (Holloran *et al* 2010).

While populations of the greater sage-grouse presently appear stable in the western US, there is a growing concern surrounding the potential for decreased survival in the face of increased wind energy development in the western US (Lebeau *et al* 2014, 2017b). Resultingly, conservation managers have proposed a wide array of mitigation strategies that fall along all steps of the mitigation hierarchy (Johnson *et al* 2007). In terms of avoidance, planners have suggested placing areas off-limits to development, as 28% of developable land in Wyoming are in greater sage-grouse core areas (Jakle 2012). Wyoming State guidelines state that no wind energy development should occur within sage-grouse core areas, and that development should be at least 0.4 km from the perimeter of occupied leks outside of core areas (Lebeau *et al* 2017). For minimizing impacts, seasonal restrictions on construction activities could be imposed and site design could be modified (i.e. spacing of turbines). For instance, some studies recommend caution when designating buffer sizes <1.5 km to avoid measurable impacts from wind turbines on greater sage-grouse and their broods (Lebeau *et al* 2017). Furthermore, wind energy infrastructure such as powerlines may reduce habitat suitability and survival of greater sage-grouse, and thus minimizing design features that attract predators is warranted (Lebeau *et al* 2019). Finally, some wind projects have proposed compensatory mitigation—West Butte Wind Project in Oregon—which includes providing restoration and enhancement of over 9000 acres of greater sage-grouse habitat on BLM-administered land and providing funds to the country of conservation easement purchases for greater sage-grouse management (Jakle 2012). Wind energy facility design and compensatory mitigation may be successful, given that short-term impacts to greater sage-grouse have been variable based on recent studies (Lebeau *et al* 2014, 2017).

4. Conclusion

The 'green energy' era in the American West is here to stay and increasing substantially each year. This growth is a combination of aggressive energy policies and social acceptance of alternative energy technologies (Hamilton *et al* 2018). However, our review revealed that the ecological effects of utility-scale renewable energy development on wildlife are still fraught with substantial uncertainties, largely due to the lack of BACI studies and mitigation strategies being mostly species-specific. In addition, some have suggested that long-term and large-scale ecological impacts of utility-scale renewable energy development are 'challenging to mitigate' (Moore-O'Leary *et al* 2017). Despite these challenges, our review identified that viable opportunities still remain for prioritizing wildlife conservation in the face of increasing renewable energy development. For instance, our review suggests that sustainable development may require: (1) using decision support tools that weigh major conservation priorities identified from previous research to identify and select sites and facility designs that minimize impact, (2) applying novel mitigation techniques developed for existing installed facilities (i.e. automated wildlife deterrence and detection system), (3) incorporating BACI studies that provide managers with conservation metrics (i.e. wildlife space use and behavior) for evaluating different future development land-use scenarios, and (4) improving our understanding of the effects of solar development on poorly studied taxonomic groups such as non-volant wildlife. Consequently, future developments could avoid predicted high risk areas (i.e. core wildlife habitat) via site selection in already disturbed environments, incorporating modified facility designs that allow for safe wildlife passage, and identifying offsite habitats that provide effective compensatory mitigation for both volant and non-volant wildlife.

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