The Energy Footprint: How Oil, Natural Gas, and Wind Energy Affect Land for Biodiversity and the Flow of Ecosystem Services

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Society's growing demand for clean and abundant energy has repercussions for biodiversity and human well-being. Directives for renewable energy, energy security, and technological advancements such as horizontal drilling in conjunction with hydraulic fracturing have spurred a rapid increase in alternative and unconventional energy production over the last decade. Given the projected increases in oil, gas, and wind energy development, we synthesize and compare known impacts on wildlife mortality, habitat loss, fragmentation, noise and light pollution, invasive species, and changes in carbon stock and water resources. The literature on these impacts is unevenly distributed among energy types, geographic regions, and taxonomic groups. Therefore, we suggest priorities for research and practice, including using a landscape approach to predict and plan for the cumulative effects of development. Understanding the full consequences of energy production is necessary for meeting demand while also safeguarding the ecological systems on which we depend.

Keywords: energy sprawl, habitat loss, habitat fragmentation, land use, landscape conservation

Global energy production is in the middle of a substantial transformation. Energy use is expected to increase annually, with fossil fuels meeting the majority (78%) of that demand in the United States and most other countries (EIA 2013a). The recent trend toward developing more domestic energy sources is driven in part by political instability in some oil-rich nations and in part by the desire to maintain energy security (Yergin 2006). Technological advancements such as horizontal drilling in conjunction with hydraulic fracturing have made extraction of shale resources economically viable, promoting a rapid increase in unconventional energy production over the last decade (Kerr 2010). Concurrently, recognition of the potential social and biological ramifications of climate change is driving the push to regulate emissions by expanding carbon-neutral sources of energy, such as solar and wind power (Pimentel et al. 2002). This shift toward domestic energy development is well underway: For example, in the United States, wind energy production has increased 23-fold since 2000, and natural gas production has risen by almost 21% over the last two decades (EIA 2012). The consequences of this changing energy portfolio for biodiversity and human well-being, however, are not straightforward.

In comparison with oil and gas (and all fossil fuels), wind energy has the lowest lifecycle emissions of carbon dioxide and other greenhouse gases (Jacobson 2008). Many studies have indicated a significant loss in global biodiversity and ecosystem services as a result of increasing global temperatures from the use of fossil fuels (McDaniel and Borton 2002). As such, wind energy development is being promoted as a "clean" alternative. However, this perspective often overlooks the ever-growing impacts of energy development on the landscape, which have been termed *energy sprawl* (McDonald et al. 2009). Like oil and gas, wind energy requires a network of roads, transmission lines, and associated infrastructure to capture and transport the power. Information on the current and projected impacts of oil, gas, and wind energy development on habitat for biodiversity and land-based ecosystem services is scarce (figure 1) and warrants further investigation, given the potential of energy development to transform natural and human-dominated landscapes (figures 2 and 3).

Here, we review existing literature on the impacts of oil, gas, and wind energy development on various local and landscape-level indicators that may influence terrestrial biodiversity and ecosystem services, including wildlife

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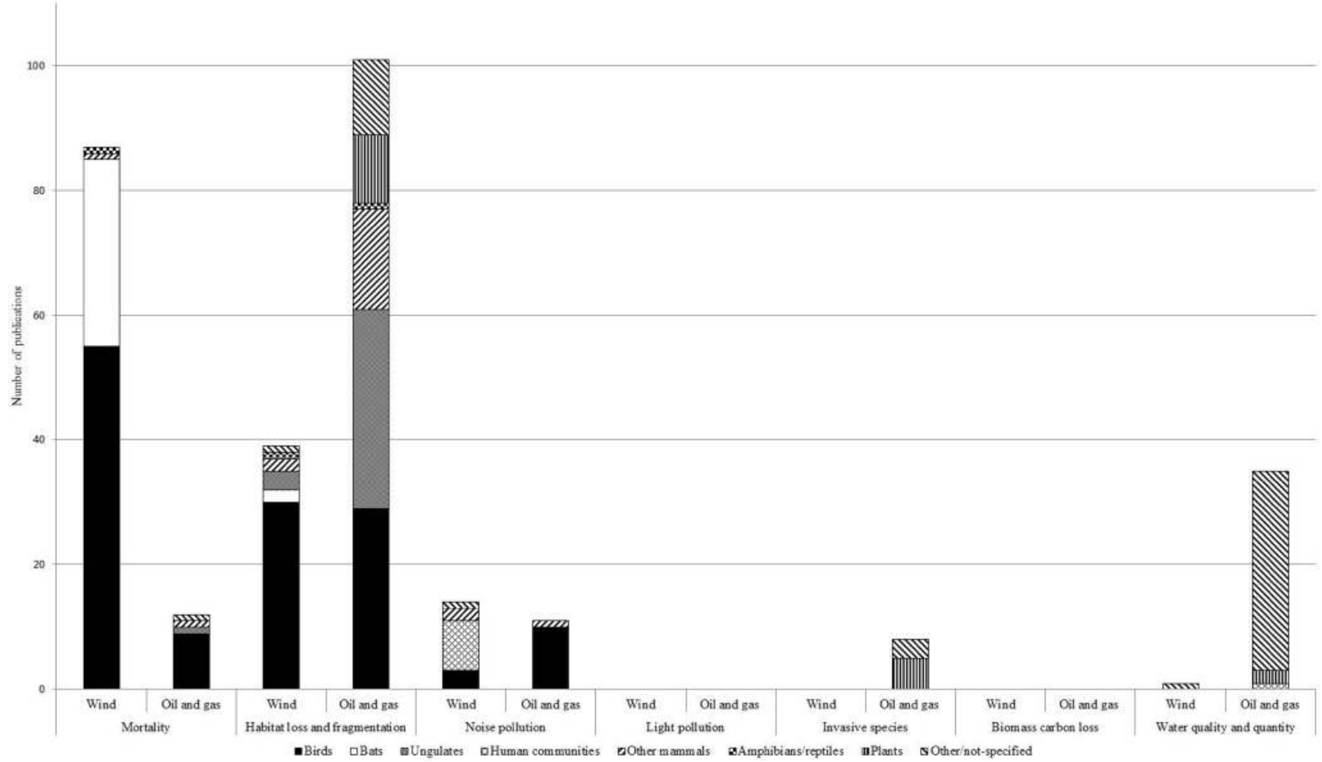

*Figure 1. The number of scientific publications reporting the impacts of terrestrial wind energy, oil, and natural gas development on seven indicators of biodiversity and ecosystem services, tallied by taxonomic group. The articles were obtained from a systematic Web-based search using keywords (indicators) and modifiers (energy type) in the Web of Knowledge (*www.webofknowledge.com*).*

Figure 2. Characteristic images of energy sprawl on a rural landscape. (a) Oil and gas field in Wyoming. Photograph: David Stubbs, The Nature Conservancy. (b) Wind energy facility in Pennsylvania. Photograph: Mark Godfrey, The Nature Conservancy.

mortality, habitat loss, habitat fragmentation, noise and light pollution, invasive species, and changes in carbon stocks and freshwater resources. These indicators were chosen as surrogates for measured impacts on species diversity and the provision of some ecosystem services, which are site specific and difficult to obtain. These indicators are not necessarily equally important to biodiversity and ecosystem services, and they are manifested in different ways, depending on energy type (table 1). We expect that the value of these effects will vary, depending on the ecological and social context of the development. We summarize current knowledge and highlight key areas for additional inquiry for each indicator. Finally, we suggest strategies for evaluating, predicting, and planning for the impacts of energy development on the landscape in light of emerging policy issues.

This synthesis is focused on the local wind farm and oil or gas field at which

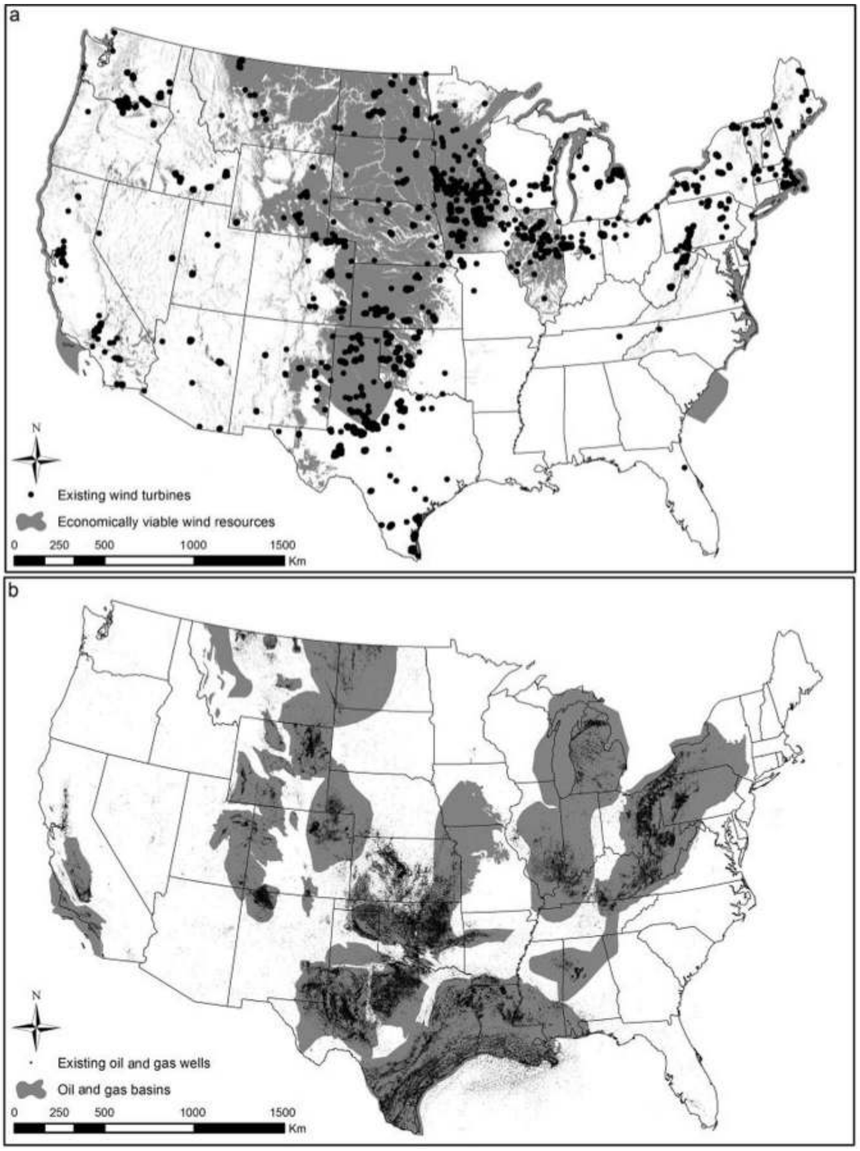

Figure 3. The existing extent and potential future expansion of energy development in the contiguous US. (a) Existing wind energy facilities (black dots; FAA 2013) and areas with suitable wind resources for industrial scale wind energy development (gray shading; AWS TrueWind and NREL 2013). (b) Existing oil and natural gas wells (black dots; Biewick 2008) and areas with suitable geological resources for future extraction (gray shading; EIA 2013c). Abbreviation: km, kilometers.

development occurs but does not incorporate the entire life cycle of energy development and use. We emphasize that all stages of energy use have important consequences for nature and society, and the effects of the latter phases of this life cycle have and should be addressed elsewhere (Gagnon et al. 2002, Fthenakis and Kim 2009, Burnham et al. 2012). We deliberately restricted the scope of our study to the initial extraction phase, in response to emerging concerns over the expanding footprint of energy development on land and land-based resources (McDonald et al. 2009). This is the phase that is most likely to result in land-use change, the clearing of native vegetation, and local adverse effects on wildlife and the provision of ecosystem services (table 1). It is also the scale at which environmental impact assessments are focused and at which permitting and mitigation requirements are determined.

We assessed the existing literature on worldwide land-based impacts on biodiversity and selected ecosystem services from terrestrial oil, natural gas, and wind energy development using standardized searches in the Web of Knowledge. Only empirical, peer-reviewed articles published prior to 1 November 2013 were included in our review. The searches were conducted using combinations of keywords and modifiers. The keywords included *oil*; *natural gas*; *wind energy*; and various synonyms or specific infrastructure, such as *pipeline*, *road*, and *turbine*. The modifiers included the following indicators of habitat quality for biodiversity and ecosystem services (and their synonyms): *habitat loss and fragmentation*, *wildlife mortality*, *noise and light pollution*, *invasive species*, *biomass carbon stock*, and *water resources*. We included articles on pipelines, power lines, and roads only if they were directly associated with oil and gas or wind energy during the extraction phase. In addition to the energy types and indicators studied in the resulting articles, we recorded the year of publication, the geographic location or locations, and the taxonomic group or groups that were investigated. Note that our analysis was focused only on the direct and indirect impact of the footprint associated with development during the production and early on-site portion of the transmission phases.

We identified 276 articles that met our search criteria; 117 articles were focused only on wind energy, 158 articles were on the impacts of oil or natural gas, and one article reported on the effects of both types of energy development. Thirty-seven countries were represented, but the majority of the literature came from North America, with 47% of the articles based on research in the United States and 18% from Canada (figure 4). Research that occurred in the United States represented approximately 43% of the wind energy studies and 50% of the oil and gas studies. The majority of wind energy studies in the United States were from California (31%), whereas the majority of oil and gas studies were from Wyoming (34%). In Canada,

Table 1. The shared and disparate effects of wind and oil and gas development on biodiversity and ecosystem services, at the extraction phase of energy development and production.

	Wind	Oil and gas
Habitat loss and fragmentation	Roads, turbine pads, transmission lines, meteorological towers, substations, operation buildings	Roads, well pads, pipelines, compressors, reserve pits, evaporation ponds
Potential mortality	Turbines, transmission lines, roads, meteorological towers, buildings	Roads, reserve pits, evaporation ponds, flares, power lines, buildings
Noise pollution	Turbines, roads, operation buildings, substations, construction equipment	Roads, drill rigs, construction equipment, pump jacks, compressors, flare stacks, fracking equipment, aerial coolers, generators
Light pollution	Turbines, roads, operation buildings, substations, construction equipment	Roads, drill rigs, construction equipment, flares,
Invasive species	Roads, turbine pads, transmission lines, temporary disturbance	Roads, well pads, pipelines, power lines, temporary disturbance
Carbon stock loss	Roads, turbine pads, transmission lines, meteorological towers, substations, operation buildings,	Roads, well pads, pipelines, compressors, reserve pits, evaporation ponds
Impervious surfaces	Roads, turbine pads, transmission lines, meteorological towers, substations, operation buildings	Roads, well pads, pipelines, compressors, reserve pits, evaporation ponds
Water consumption	Dust suppression	Fracking operations, drilling operations, reserve pits, evaporation ponds, dust suppression

the vast majority of the wind and oil and gas studies were located in Alberta (80%; figure 5).

Research on the land-based impacts of oil, gas, and wind energy is not necessarily proportionate to existing energy reserves or capacity. For example, four of the top five wind-producing states (i.e., Texas, Iowa, Oklahoma, and Kansas) contain 30% of the existing wind energy capacity in the United States (EIA 2013b), but only 16% of the wind energy studies were located in those states. In contrast, California contains only about 9% of the national wind capacity, but 31% of the wind energy studies were conducted in this state. Texas produces almost 43% of the nation's crude oil (EIA 2014a) and 32% of the nation's natural gas (EIA 2012), but only seven (9%) of the oil and gas studies were in that state. This is in contrast to Wyoming, which produces less than 3% of the nation's crude oil (EIA 2014a) and 9.7% of the nation's natural gas (EIA 2012) but which was the location of 34% of the studies (figure 5). An important driver of this disparity may be that the high rate of development in the sagebrush–steppe ecotype corresponds with the habitat of the greater sage grouse (*Centrocercus urophasianus*), a species of conservation concern.

There are notable differences among energy types in regard to the taxonomic and topical focus of articles addressing the impacts of energy development. In about 85% of the wind energy studies, impacts on birds and bats were investigated, whereas in only 30% of the oil and gas studies was the focus on birds (no oil and gas studies were completed on bats). There was also substantial variation in the number of studies published on each of the indicators (figure 1). Direct mortality, habitat loss, and fragmentation were commonly addressed in impact studies, but there were no studies on light pollution or biomass carbon stock for either industry. Nor did we find any studies on the impacts on invasive species from wind energy. The following sections draw on this comprehensive literature review to summarize existing knowledge on impacts on biodiversity, habitat quality, and important ecosystem services from oil, natural gas, and wind energy development. Here, we make comparisons among energy types in terms of their potential impacts, but we recognize that the limited nature of the available data prevents us from drawing conclusions about the severity of these impacts or from making assertions on the differences among energy types.

Impacts on biodiversity and ecosystem services

The following sections synthesize and compare known impacts on wildlife mortality, habitat loss, fragmentation, noise and light pollution, invasive species, and changes in carbon stock and water resources. In addition, we recommend priorities for research and practice, where possible.

Wildlife mortality. Our search returned 79 papers categorized as wind energy mortality studies, although many were specific to individual taxa or faunal groups or contained specific methodological techniques. All but one of these were focused on mortality to birds and bats. The 35 mortality studies from the United States represented only 13 states. Numerous reviews have synthesized data on mortality from wind turbines (Loss et al. 2013, Smallwood 2013), despite a lack of peer-reviewed publications on this topic. For instance, only 3 of the 60 postconstruction studies reviewed by Smallwood (2013) were published in peer-reviewed journals.

Published studies demonstrate that energy development can result in wildlife mortality because of collision, contamination, or electrocution. In addition to turbines, wind facilities employ meteorological towers that are known to result in avian collision mortality (Erickson et al. 2005) but that are often overlooked during mortality studies. Wind energy facilities share sources of mortality with oil and gas development, including vehicle collisions and power line electrocution; the magnitude of these effects varies as a function of the

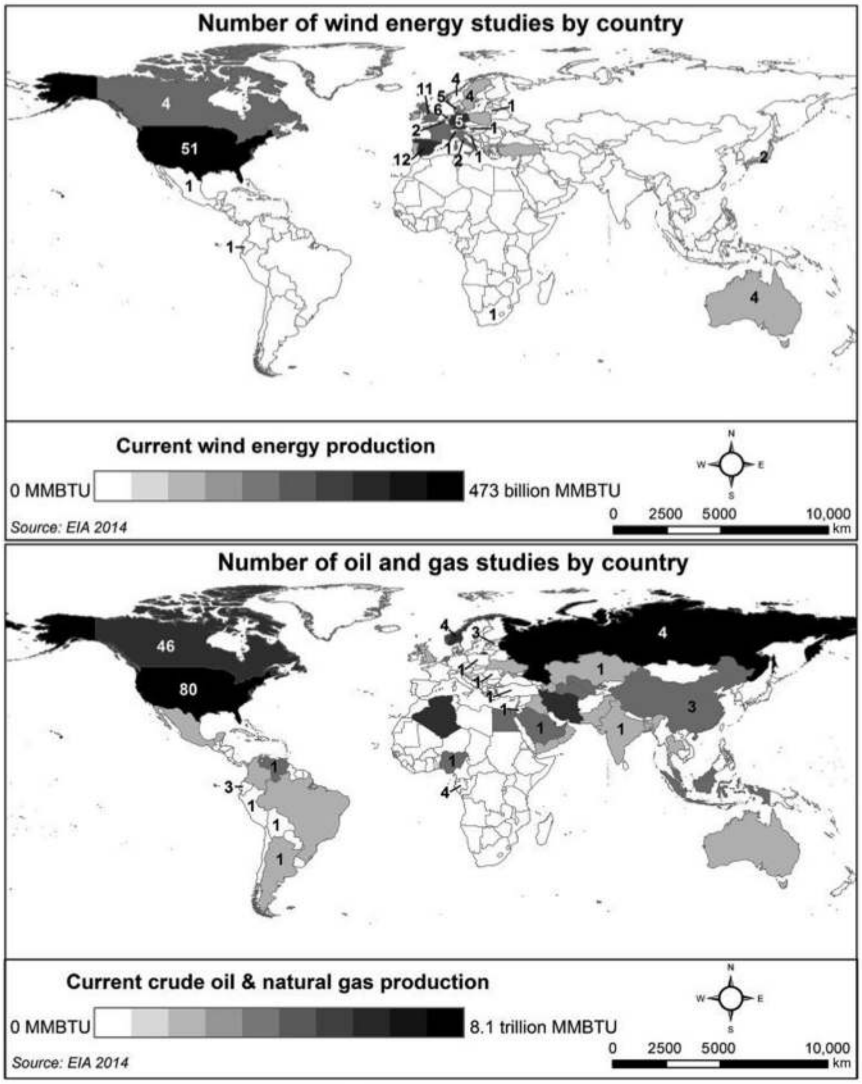

Figure 4. The number of published, peer-reviewed studies on the impacts of oil, gas, and wind energy on selected indicators of biodiversity and ecosystem services by country, relative to current annual production (EIA 2014b). Abbreviations: km, kilometers; MMBTU, million metric British thermal units.

surrounding habitat and focal taxa. For example, as much as 17% of avian mortality was attributed to vehicle collisions at a Minnesota wind farm (Higgins et al. 2007). Power line electrocutions are more common among large birds, such as raptors, because they are capable of bridging the connection between two different phase or hot and grounded wires. Waterfowl and other birds that exhibit poor maneuverability are more likely to collide with stationary structures such as power lines (Bevanger 1998). Power line fatality rates are difficult to quantify and are often underestimated (Bayne and Dale 2011), but avian mortalities associated with power lines can be reduced through proper siting, outfitting transformers with protectants, and the use of line markers.

Mortality from wind energy could lead to localized population-level impacts, and the cumulative result of wind energy with other anthropogenic sources of mortality may cause widespread declines in avian and bat populations. All of these impacts require more consistent and rigorous monitoring. Obtaining, synthesizing, and communicating reliable information on mortality rates under different scenarios (e.g., geographical location, climate, topography, presence of species of conservation concern) is fundamental to identifying creative engineering and environmental solutions to minimize mortality. However, the literature reveals persistent concerns regarding the inconsistency, poor rigor, and lack of transparency of mortality studies at wind facilities worldwide (Kuvlesky et al. 2007). The majority of data is held by hired consultants and is rarely publicly available. To this end, the American Wind Wildlife Institute and its partners are developing a comprehensive data information and management tool that will expand the availability of wind–wildlife data. The research information system will allow for the synthesis and analysis of data while protecting the proprietary nature of the studies.

We found only 12 studies in which wildlife mortality from oil and natural gas development was investigated, but these articles suggest that wildlife mortality may be a significant and underrepresented problem. Sources of mortality unique to oil and gas development include contamination from reserve pits and evaporation ponds used to store the byproducts of drilling. Most regulations require these pits be netted to prevent entry by wildlife; however, this does not always occur. Studies have shown relatively high numbers of bird carcasses in pits, such as an average of 8.4 avian fatalities per unprotected reserve pit each year (Trail 2006). In addition, massive avian mortality events have occurred as a result of gas flare stacks at refineries (Bjorge 1987). Flare stacks and gas compressors, which emit heat, flames, and toxins, are common within oil and gas fields; however, no research has been performed on wildlife mortality associated with this infrastructure. This could be a significant source of impacts as shale oil development becomes more common in remote locations. Although oil can be stored in tanks indefinitely after drilling, natural gas must be immediately piped to a processing facility.

Habitat loss and fragmentation. Habitat loss is the leading cause of species extinction and other negative impacts

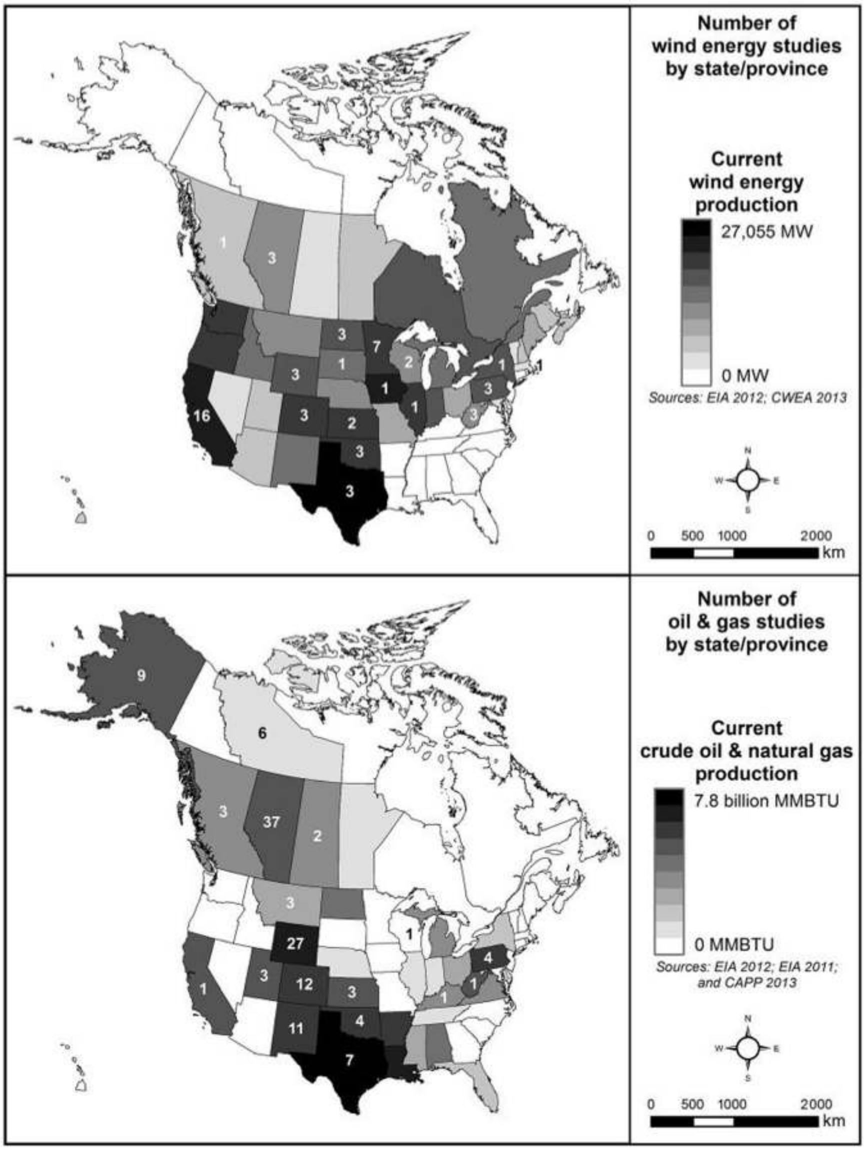

Figure 5. The number of published, peer-reviewed studies on the impacts of oil, gas, and wind energy on selected indicators of biodiversity and ecosystem services by US state and Canadian province or territory relative to current annual production (EIA 2011, 2012, CWEA 2013, CAPP 2014). Abbreviations: km, kilometers; MMBTU, million metric British thermal units; MW, megawatts.

on biodiversity (Pimm and Raven 2000) but has received relatively little attention in the energy development literature (figure 1). Habitat losses from energy development include well pads, turbine pads, roads, buildings, transmission lines, and surface pipelines. The surface area required by wind energy facilities and oil and gas development is highly variable and dependent on numerous site-specific factors. By 2030, wind is forecasted to require substantially more land area (72.1 hectares [ha]) than oil and natural gas (44.7 and 18.6 ha, respectively) per terawatt of power produced in the United States (McDonald et al. 2009). In Colorado and Wyoming, a relative comparison of habitat loss based on existing development indicates that wind and oil and gas are comparable per unit area but that wind energy would require almost twice the footprint of oil and gas per unit energy produced (Jones and Pejchar 2013). However, the productivity of oil and gas wells is far more variable than wind energy. Therefore, understanding the trade-offs between energy production and environmental footprint depends in part on the energy yields in a particular landscape. For both energy types, habitat loss from roads is substantial, often accounting for the largest proportion of land-use change (Denholm et al. 2009).

As the demand for energy continues, all types of energy development will expand to increasingly remote areas, requiring more miles of roads, transmission lines, and pipelines. Wind energy can be selectively developed on sites that are already disturbed (e.g., reclaimed mines, agricultural fields, industrial sites) because of the widespread availability of this resource (Kiesecker et al. 2011). In contrast to traditional gas development, shale gas is developed with multiple horizontal wells that can reach out 1524 meters or more from one well pad (Soeder and Kappel 2009). Although unconventional gas has larger pads on average, they employ multiple lateral wells on each pad and are able to drain an area much larger than from shallow gas pads (200–400 ha versus 4–32 ha). The lateral reach of shale gas wells means that there is more flexibility in where well pads and infrastructure can be placed relative to conventional gas (Mooney 2011).

Compared with other energy sources, such as hydroelectric or coal, oil, gas, and wind require less infrastructure but result in higher levels of habitat fragmentation, because their impacts are geographically scattered rather than concentrated (McDonald et al. 2009). Data on habitat loss and fragmentation as a result of wind energy development are limited to only 37 peer-reviewed articles, despite repeated mention of potential impacts in the literature (Arnett et al. 2007, NRC 2007). In Europe, the loss of habitat and fragmentation associated with wind energy facilities is considered a greater impact than are collision-related fatalities on bird populations (Gill et al. 1996).

Research on the implication of habitat fragmentation from energy sprawl has been focused almost exclusively on birds and ungulates. Decreased lek attendance and increased avoidance in prairie chickens (*Tympanuchus* spp.) and

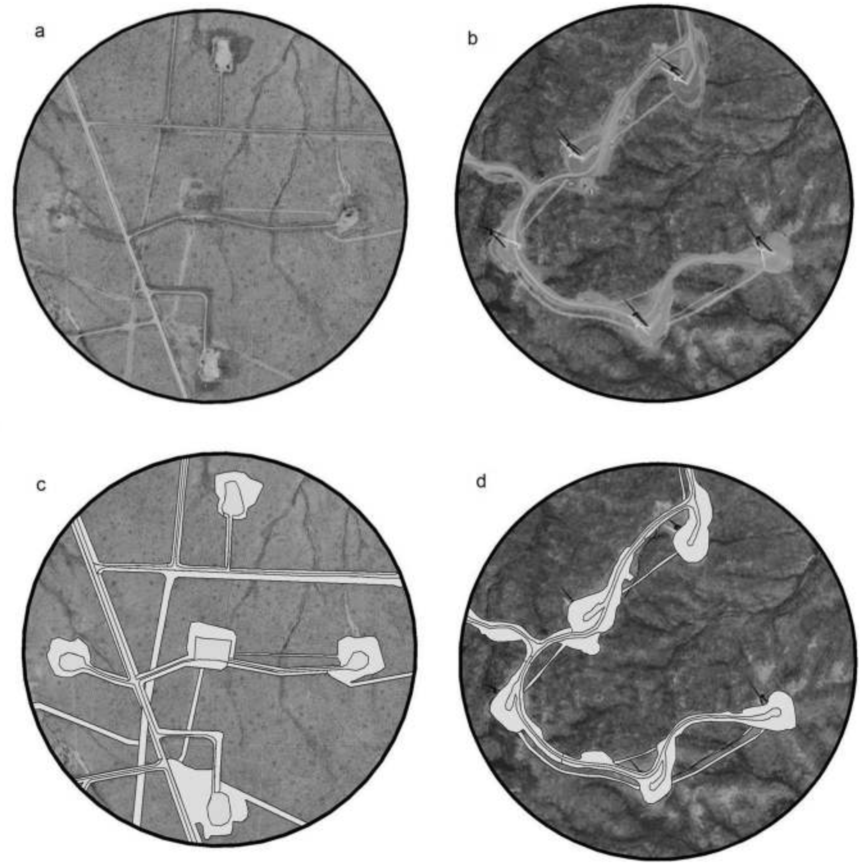

Figure 6. Aerial imagery of (a) a natural gas field and (b) a wind energy facility. Each image includes five turbines or well pads plus the associated infrastructure within a 1-kilometer diameter circular plot. The environmental footprint of each site has been digitized using geographic information systems (c, d). This geospatial data, paired with site-level data from these locations or similar areas, can be used to estimate relative impacts on indicators such as habitat loss, fragmentation, impervious surfaces, annual potential wildlife mortality, invasive plant infestation, changes in carbon stocks, and changes to water resources. The production of the five natural gas wells is approximately 2.6 times the production of the five wind turbines; therefore, energy production should also be taken into account when calculating the relative impact of alternative energy sources.

greater sage grouse has been attributed to fragmentation in natural gas fields and from power lines (Doherty et al. 2008, Pruett et al. 2009). Increasing oil and gas well densities have been attributed to declines in sagebrush obligate songbirds in Wyoming (Gilbert and Chalfoun 2011). Similar impacts are expected from wind development, but the only empirical study to date indicated no negative effect on survival of female prairie chickens. The authors suggest that this may be a result of decreased predator abundance because of wind energy development (Winder et al. 2013).

Several studies demonstrate adverse effects on ungulates because of habitat fragmentation from oil and gas development. Mule deer (*Odocoileus hemionus*) habitat selection preferences are altered, and this species fails to habituate to the presence of natural gas wells (Sawyer et al. 2006); pronghorn (*Antilocapra americana*) densities decrease near energy development (Easterly et al. 1991); and the population decline of the endangered woodland caribou (*Rangifer tarandus tarandus*) in Alberta is attributed in part to petroleum development (AWCRT 2005). In contrast, in only one small-scale study in Oklahoma has ungulate response been investigated from wind turbines (Hebblewhite 2011).

Given the lack of empirical data on the fragmentation impacts of wind energy on wildlife populations, development siting and design decisions are being made on the basis of inferred impacts from other land uses, such as transportation, oil and gas, and residential development. Because of the challenge of collecting empirical data on the impact of energy development on habitat fragmentation and biodiversity at such large scales, aerial imagery could be a powerful tool for calculating a comparable metric of habitat loss and fragmentation between energy developments and across alternative types of energy production (figure 6).

Noise and light pollution. Noise and light pollution are widely acknowledged as sources of disturbance to humans and other species, contributing to habitat degradation and wildlife displacement, and masking auditory and visual life-history traits essential for survival and reproduction. However, a common framework for estimating impacts in which the intensity, frequency, and timing of noise and light are accounted for is lacking (Francis and Barber 2013). We found 23 articles on noise pollution (13 from wind energy, 10 from oil and gas), but none on light pollution. A substantial challenge of these studies is isolating the impacts of noise or light from confounding stimuli that are often associated with or create the noise (Francis et al. 2011). The loudness of the noise or brightness of the light is less important than the consistency of both types of pollution. For instance, a relatively quiet noise that is irregular and unpredictable could be perceived as a threat. Although wildlife may habituate to a consistent noise, there may still be fitness costs to individuals (Francis and Barber 2013).

The sources of noise within an oil and gas field include vehicle traffic, drill rigs, fracking operations, production wells, pump jacks, aerial coolers, compressors, flare stacks, and generators. The noise level estimates in oil and gas fields range from 59 decibels (dB) at drilling rigs to 70 dB at large gas compressors (Blickley et al. 2012). Wind turbines create aerodynamic noise from the blades passing through the air, and noise propagation is positively associated with wind speed. A modern industrial-scale wind turbine may reach a maximum noise level of about 78 dB at 15 meters (Rogers et al. 2006). However, the impact of this noise can be tempered by the sound of the wind. Other sources of noise at a wind energy facility include temporary construction activities, vehicle traffic, and noise associated with the substation and operation buildings.

Nighttime light propagation from oil and gas fields includes gas flares, vehicle headlights, and temporary disturbance from 24-hour drilling barracks. The level of light pollution in oil and gas fields varies greatly, depending on the amount of human activity and necessity for gas flaring. Conversely, utility-scale wind turbines must be lit to comply with Federal Aviation Administration requirements. The number of turbines lit varies at wind facilities on the basis of numerous factors including location and topography. Environmental responses to noise and light pollution are difficult and inefficient to detect empirically. Spatially explicit models such as SPreAD-GIS and NMSim could shed light on the relative impacts of energy development on these types of pollution under different land-use or land-cover scenarios.

Invasive species. We found only eight studies on the impact of invasive species from oil and gas and none on the topic for wind energy. The broader literature suggests that biological invasions can reduce species richness and biodiversity and cause severe impacts on ecosystem processes and human well-being. Invasive plants and animals may compete with native species, alter disturbance regimes, or reduce the quality of the land for secondary uses, such as grazing and agriculture (Pimentel 2002).

Invasive and nonnative plants may be introduced via various pathways during the construction of energy developments. Vehicles may transport nonnative propagules, soils brought onsite may be infected with weeds, and reseeding activities may result in the inadvertent introduction of invasive plants. Developers often employ best management practices to prevent the introduction of invasive species and control invasions if establishment occurs. However, the presence of freshly disturbed soils and the continued use of roadways perpetuates the risk of invasions for years after construction (Brooks 2007). Empirical data regarding the presence or absence and the degree of invasive species associated with energy development is limited, and monitoring efforts are often proprietary in nature. The consensus among these studies was that oil and gas development and their associated disturbances may facilitate the establishment of nonnative plants, particularly in arid environments, such as western North America. Given the similarities in footprint and distribution, the same can be expected of wind energy. Where empirical data are not available, we suggest using proxies (e.g., road length, area of temporary disturbance) combined with empirical data to estimate the extent of existing invasions or to predict the relative invasibility of a proposed development (Jones and Pejchar 2013).

Carbon sequestration. A widely espoused benefit of wind energy is its substantial savings in greenhouse gas emissions, including carbon dioxide. Carbon sequestration is the process of soils and plants removing carbon dioxide from the atmosphere and storing it as a result of photosynthesis, thereby regulating the atmospheric concentrations of carbon dioxide, which affect the global climate. However, the replacement of vegetation and topsoil by impermeable surfaces associated with energy development reduces the potential for natural carbon sequestration and increases carbon emissions through the loss of biomass and increased soil erosion (Bruce et al. 1999). The extent to which energy development affects carbon losses from vegetation and soils is not clear; we did not find any empirical peer-reviewed articles on the subject within our search timeframe. Jones and Pejchar (2013) suggest that, in Colorado and Wyoming, oil and gas are responsible for a greater loss of biomass carbon that wind, largely as a result of the tendency for oil and gas to be developed in areas with more carbon-rich land cover. As shale gas development is projected to expand in the tropics of South America, Africa, and Asia, the impact to biomass carbon from land use will need to be considered. In light of the substantial threat of global climate change to nature and society, understanding the impact of these losses on the overall emissions debt of energy development is crucial for evaluating the relative greenness of alternative sources of energy.

Water resources. Water resources, or the quality and quantity of water available to aquatic ecosystems and human consumption, can be adversely affected by the development of oil, gas, and wind energy facilities. The direct loss or consumption of water associated with wind energy construction and operation is very small or nonexistent. Some oil and gas wells, however, may require between two and seven million gallons of source water during the drilling process (Entrekin et al. 2011). Water is used as a lubricant during drilling and may be reinjected during a process known as *secondary recovery*, which requires the injection of water or other liquids to increase pressure and improve productivity. The majority of the 35 articles that we found related to water resource impacts from oil and gas development were focused on the quality of the surrounding water resources rather than on the quantity of water consumed.

Advances in horizontal drilling technology and hydraulic fracturing have helped to expand natural gas production in the United States. Fracking has unlocked natural gas supplies in shale and other unconventional formations across the country; however, the process requires large volumes of water (Entrekin et al. 2011), and the fluids used to fissure rock formations contain numerous chemicals that could have detrimental impacts on water quality and downstream communities. Despite widespread concern about these environmental impacts, little is known about the impacts of energy development on aquatic biota; we found only four peer-reviewed studies on the impacts specific to aquatic organisms from energy development (figure 1). However, degradation of water quality is an implied impact in most of the 29 studies categorized as *unspecified* in our review. The substantial increase in water use associated with oil and gas development is also of concern, because water consumption alters stream flows and affects aquatic ecosystem function (Dauwalter 2013). Because natural gas is seen as a bridge to a low carbon economy, it will be crucial to assess freshwater impacts resulting from the increased use of fracking in particular (Entrekin et al. 2011).

Even though data on impacts are limited, oil and gas development probably causes greater impacts on water resources than wind energy development because of the large volume of water used during the drilling process and the potential impacts on water quality. Regardless of type, however, energy development creates additional impervious surfaces that prevent the infiltration of water into the soil. Greater runoff contributes to the degradation of riparian areas through increased sediment load, interferes with the natural processing of pollutants, and reduces the amount of groundwater available to natural and human communities. As the impervious surface increases, native species richness and abundance tend to decrease, and human adapted and invasive species increase (Hansen et al. 2005). Particularly in the western United States, both petroleum and wind development are expanding rapidly in arid regions, making the question of to what extent alternative forms of development impact water quality and compete for water with other users extremely relevant.

Conclusions

The goals of energy development and conservation need not be mutually exclusive, but they will require a sea change in how we think about and plan for development (Kiesecker et al. 2010). Proactive thinking about how to avoid or minimize conflict between these goals at all stages—citing, construction, extraction, mitigation, and restoration—will be crucial. Importantly, this approach will also require greater investment in offsets (compensating conservation actions) to address residual project impacts and deliver net gains for nature (Kiesecker et al. 2009). To meet this challenge, public land managers, private landowners, and policymakers need more complete information on the impacts of energy development to guide decisions. Much of the existing research and monitoring is species or location specific. As such, the results of these studies are applicable under particular circumstances but do little to set regional, national, or global science and policy agendas based on quantifiable impacts comparable across industries. We found that published research on energy impacts is clustered geographically but not necessarily in proportion to development intensity and that information on some impacts (e.g., mortality) is derived from only a handful of energy installations. An understanding of the full suite of trade-offs among alternative energy development scenarios that incorporate local and landscape level impacts and can be applied to populations, communities, and ecosystems is needed to make informed policy decisions.

The first step to meeting this need is supporting research and encouraging monitoring that fills key information gaps. We recommend the following as top priorities for researchers and practitioners:

Adopt a landscape perspective to assessing impacts on biodiversity and ecosystem services. The scientific and regulatory communities require a better understanding of how the indicators described above affect populations, ecosystems, and society. Because initiating new location and species-specific studies is not practical for every proposed energy project, we recommend complimentary analyses that quantify the impacts of energy development on indicators from a landscape perspective. Understanding the characteristics of the landscape that increase or decrease the severity of disturbances will aid in the responsible design of projects at a regional scale and will result in more comprehensive impact estimates. This type of analysis is relatively inexpensive and allows investigators to draw inferences over a larger geographic scale and for a wide selection of predictor variables. For example, aerial imagery can be used to obtain accurate measurements of the habitat loss and fragmentation resulting from energy development across a diversity of landscapes (figure 6). By incorporating existing data layers, development plans, and landscape characteristics, estimates of the impacts of energy sprawl under alternative land-use scenarios can be obtained (Jones and Pejchar 2013). This approach has particular utility in an energy development context, in which there is a paucity of data on impacts on wildlife, ecosystem processes, and human well-being. This strategy aligns well with the recognition that mitigation programs need to move away from site-based, piecemeal mitigation—which often results in a patchwork of isolated, degraded, and difficult-to-manage habitats—to an approach that is more ecologically relevant in scale and is capable of comprehensively accounting for cumulative impacts affecting an entire region. For example, compensatory mitigation in the United States now requires the adoption of a landscape approach to identify and facilitate investment in key regional conservation priorities and to ensure early integration of mitigation considerations in project planning and design (Presidential Executive Order No. 13604; Clement et al. 2014). Other countries are also following this trend. For example, Colombia has passed a new mitigation regulation (Colombian Resolution 1517 of 2012) that requires that both the amount and location of compensation for development impacts are based on a series of landscape features (Saenz et al. 2013).

Model the propagation of noise and light pollution from sources in energy developments and identify the landscape characteristics (e.g., topography, elevation, land cover) that may affect these sources of disturbance. The impacts of noise and light are particularly difficult to quantify, and empirical data collection is not efficient. Using existing geospatial models to predict the propagation of noise (and potentially light) across a landscape is a valuable tool to determine the relative impacts on both the human and natural landscapes. Such information is relatively simple to obtain and would be valuable for development planning and applying mitigation measures (Francis et al. 2011).

Assess the probability and extent of the spread of invasive species using linear rights-of-way and areas of temporary disturbance as a proxy. Invasive species can change disturbance regimes, such as fire dynamics, and degrade habitat quality for wildlife. Detecting and mapping infestations requires extensive fieldwork, and assessing impacts can be difficult. Using empirical data, expert knowledge, and landscape and development characteristics, invasion potential can be assessed remotely or predicted for different developments, thereby allowing managers to focus their efforts in high-risk areas.

Quantify changes in ecosystem services as a result of energy development. The additive (oil and gas) or confounding (wind) effects of the loss of carbon storage or sequestration as a result of energy development have been largely overlooked. Similarly, potential threats to water resources from natural gas development have only recently entered the public spotlight, and these effects are still unclear in many regions. Requiring monitoring to understand how development affects ecosystem services and translating these impacts into economic terms will be crucial for decisionmakers evaluating the trade-offs of various development scenarios.

Improve the quality, quantity, and transparency of pre- and postconstruction scientific assessments. Understanding which species or populations are at particularly high risk from energy-related mortality requires clear and rigorous standards for pre- and postimpact studies (Garvin et al. 2011), better access to existing data, and a broader focus on other sources of mortality. Requiring energy developers to create a comprehensive data information system that will expand the availability of monitoring data will be key. Regulations on both public and private lands should increase the requirements for postdevelopment monitoring that emphasizes sound methods in an adaptive framework (Nichols and Williams 2006). There should be a greater emphasis on indirect impacts on wildlife, such as habitat fragmentation, which over the long term, may be just as detrimental as direct mortality but which have received very little attention in the scientific literature. In addition, adaptive monitoring should be focused on species of conservation concern and ecosystem services that affect human health and well-being, such as water quality. Establishing a consistent monitoring network for each energy type across all future projects will provide the foundation for innovative research that integrates engineering with ecology to minimize undesirable impacts while meeting energy demand. Furthermore, where relatively little empirical data are available, predictive modeling that incorporates strong inference is particularly important for guiding decisionmaking and for setting priorities for future research (Nichols and Williams 2006). Given the paucity of studies outside of the United States, Canada, and Europe and projections of increased energy production in the developing countries of South America, Africa, and Asia, it will be crucial to ensure that we can both extrapolate existing knowledge and increase understanding in these regions.

As energy development increases and spreads concurrently with human population growth, understanding the consequences of alternative development scenarios for natural ecosystems and human communities is emerging as essential to the persistence of biodiversity and natural capital. Adopting the research and monitoring directives outlined above could provide the tools necessary to safeguard our natural heritage and preserve the ecological systems on which we depend.

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Supplemental material

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References cited

Arnett EB, Inkley DB, Johnson DH, Larkin RP, Manes S, Manville AM, Mason JR, Morrison ML, Strickland MD, Thresher R. 2007. Impacts of wind energy facilities on wildlife and wildlife habitat. Wildlife Society. Technical Review no. 07-2.

[AWCRT] Alberta Woodland Caribou Recovery Team. 2005. Alberta Woodland Caribou Recovery Plan, 2004/05–2013/14. Alberta Sustainable Resource Development, Fish and Wildlife Division.

[AWS TrueWind and NREL] AWS TrueWind, National Renewable Energy Laboratory. 2013. Wind data. NREL. (27 December 2014; *www.nrel.gov/gis/data_wind.html*)

Bayne EM, Dale BC. 2011. Effects of energy development on songbirds. Pages 95–114 in Naugle DE, ed. Energy Development and Wildlife Conservation in Western North America. Island Press.

Bevanger K. 1998. Biological and conservation aspects of bird mortality caused by electricity power lines: A review. Biological Conservation 86: 67–76.

Biewick LRH. 2008. Areas of Historical Oil and Gas Exploration and Production in the United States. US Geological Survey. Digital Data Series no. DDS-60-Q. (27 December 2014; *http://pubs.usgs.gov/dds/dds-069/dds-069-q/text/cover.htm*)

Bjorge RR. 1987. Bird kill at an oil industry flare stack in northwest Alberta. Canadian Field Naturalist 101: 346–350.

Blickley JL, Blackwood D, Patricelli GL. 2012. Experimental evidence for the effects of chronic anthropogenic noise on abundance of greater sage-grouse at leks. Conservation Biology 26: 461–471.

Brooks ML. 2007. Effects of land management practices on plant invasions in wildland areas. Pages 147–162 in Nentwig W, ed. Biological Invasions. Ecological Studies no. 193.

Bruce JP, Frome M, Haites E, Janzen H, Lal R, Paustian K. 1999. Carbon sequestration in soils. Journal of Soil and Water Conservation 51: 382–389.

Burnham A, Han J, Clark CE, Wang M, Dunn JB, Palou-Rivera I. 2012. Life cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. Environmental Science and Technology 46: 619–627.

[CAPP] Canadian Association of Petroleum Producers. 2014. Statistical Handbook for Canada's Upstream Petroleum Industry, October 2014. (27 December 2014; *www.capp.ca/library/statistics/handbook/Pages/default.aspx*)

Clement JP, Belin Ad'A, Bean MJ, Boling TA, Lyons JR. 2014. A strategy for improving the mitigation policies and practices of the Department of the Interior. Energy and Climate Change Task Force, Department of the Interior.

[CWEA] Canadian Wind Energy Association. 2013. Powering Canada's Future, September 2013. (27 December 2014; *www.canwea.ca/pdf/Canada%20Current%20Installed%20Capacity_e.pdf*)

Dauwalter DC. 2013. Fish assemblage associations and thresholds with existing and projected oil and gas development. Fisheries Management and Ecology 20: 289–301.

Denholm P, Hand M, Jackson M, Ong S. 2009. Land-use Requirements of Modern Wind Power Plants in the United States. National Renewable Energy Laboratory. Technical Report no. NREL/TP-6A2-45834.

Doherty KE, Naugle DE, Walker BL, Graham JM. 2008. Greater sage-grouse winter habitat selection and energy development. Journal of Wildlife Management 71: 187–195.

Easterly T, Wood A, Litchfield T. 1991. Responses of Pronghorn and Mule Deer to Petroleum Development on Crucial Winter Range in the Rattlesnake Hills. Wyoming Game and Fish Department. Completion Report no. A-1372.

[EIA] Energy Information Administration. 2011. Maps: Exploration, Resources, Reserves, and Production. EIA. (27 December 2014; *ftp://ftp.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm*)

———. 2012. Annual Energy Review, 2011. EIA. (27 December 2014; *www.eia.gov/totalenergy/data/annual/?src=Total-f5*)

———. 2013a. International Energy Outlook 2013. EIA. (27 December 2014; *www.eia.gov/pressroom/presentations/sieminski_07252013.pdf*)

———. 2013b. Net Generation from Wind by State by Sector, September

———. 2013c. EIA. (27 December 2014; *www.eia.gov/cneaf/solar.renewables/page/wind/wind.html*)

———. 2013d. Rankings: Crude Oil Production, August 2013. EIA.

———. 2014a. Natural Gas: Maps: Exploration, Resources, Reserves, and Production. EIA. (27 December 2014; *www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm*)

———. 2014b. International Energy Statistics. EIA. (27 December 2014; *www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm*)

Entrekin S, Evans-White M, Johnson B, Hagenbuch E. 2011. Rapid expansion of natural gas development poses a threat to surface waters. Frontiers in Ecology and the Environment 9: 503–511.

Erickson WP, Johnson GD, Young DP Jr. 2005. A Summary and Comparison of Bird Mortality from Anthropogenic Causes with an Emphasis on Collisions. US Department of Agriculture, US Forest Service. General Technical Report no. PSW–GTR-191.

[FAA] Federal Aviation Administration. 2013. Terrain and Obstacle Data (TOD) Team – Digital Obstacle File (DOF). FAA. (27 December 2014; *https://nfdc.faa.gov/tod/public/TOD_DOF.html*)

Francis CD, Barber JR. 2013. A framework for understanding noise impacts on wildlife: An urgent conservation priority. Frontiers in Ecology and the Environment 11: 305–313.

Francis CD, Paritsis J, Ortega CP, Cruz A. 2011. Landscape patterns of avian habitat use and nest success are affected by chronic gas well compressor noise. Landscape Ecology 26: 1269–1280.

Fthenakis V, Kim HC. 2009. Land use and electricity generation: A life-cycle analysis. Renewable and Sustainable Energy Reviews 13: 1465–1474.

Gagnon L, Belanger C, Uchiyama Y. 2002. Life-cycle assessment of electricity generation options: The status of research in year 2001. Energy Policy 30: 1267–1278.

Garvin JC, Jennelle CS, Drake D, Grodsky SM. 2011. Response of raptors to a windfarm. Journal of Applied Ecology 48: 199–209.

Gilbert MM, Chalfoun AD. 2011. Energy development affects populations of sagebrush songbirds in Wyoming. Journal of Wildlife Management 74: 816–824.

Gill JP, Townsley M, Mudge GP. 1996. Review of the Impacts of Wind Farms and Other Aerial Structures upon Birds. Scottish Natural Heritage. Review no. 21.

Hansen AJ, Knight RL, Mazluff JM, Powell S, Brown K, Gude PH, Jones K. 2005. Effects of exurban development on biodiversity: Patterns, mechanisms, and research needs. Ecological Applications 15: 1893–1905.

Hebblewhite M. 2011. Effects of energy development on ungulates. Pages 71–94 in Naugle DE, ed. Energy Development and Wildlife Conservation in Western North America. Island Press.

Higgins KF, Osborn RG, Naugle DE. 2007. Effects of wind turbine on birds and bats in southwestern Minnesota, USA. Pages 153–175 in de Lucas M, Janss GFE, Ferrer M, eds. Birds and Wind Farms: Risk Assessment and Mitigation. Quercus Press.

Jacobson MZ. 2008. Review of solutions to global warming, air pollution, and energy security. Energy and Environmental Science 2: 148–173.

Jones NF, Pejchar L. 2013. Comparing the ecological impacts of wind and oil and gas development: A landscape scale assessment. PLOS ONE 8 (art. e81391).

Kerr RA. 2010. Natural gas from shale bursts onto the scene. Science 328: 1624–1626.

Kiesecker JM, Copeland H, Pocewicz A, Nibbelink N, McKenney B. 2009. A framework for implementing biodiversity offsets: selecting sites and determining scale. Bioscience 59: 77–84.

Kiesecker JM, Copeland H, Pocewicz A, McKenney B. 2010. Development by design: blending landscape level planning with the mitigation hierarchy. Frontiers in Ecology and the Environment 8: 261–266.

Kiesecker JM, Evans JS, Fargione J, Doherty K, Foresman KR, Kunz TH, Naugle D, Nibbelink NP, Niemuth ND. 2011. Win-win for wind and wildlife: A vision to facilitate sustainable development. PLOS ONE 6 (art. e17566).

Kuvlesky WP, Brennan LP, Morrison ML, Boydston KK, Ballard BM, Bryant FC. 2007. Wind energy development and wildlife conservation: Challenges and opportunities. Journal of Wildlife Management 71: 2487–2498.

Loss SR, Will T, Marra PP. 2013. Estimates of bird collision mortality at wind facilities in the contiguous United States. Biological Conservation 168: 201–209.

McDaniel CN, Borton DN. 2002. Increased human energy use causes biological diversity loss and undermines prospects for sustainability. Bioscience 52: 929–36.

McDonald RI, Fargione J, Kiesecker J, Miller WM, Powell J. 2009. Energy sprawl or energy efficiency: Climate policy on natural habitat for the United States of America. PLOS ONE 4 (art. e6802).

Mooney C. 2011. The truth about fracking. Scientific American 305: 80–85.

Nichols JD, Williams BK. 2006. Monitoring for conservation. Trends in Ecology and Evolution 21: 668–673.

[NRC] National Research Council. 2007. Environmental Impacts of Wind-Energy Projects. National Academies Press.

Pimentel D. 2002. Biological Invasions: Economic and Environmental Costs of Alien Plant, Animal and Microbe Species. CRC Press.

Pimentel D, et al. 2002. Renewable energy: Current and potential issues. Bioscience 52: 1111–1120.

Pimm, SL, Raven P. 2000. Biodiversity: Extinction by numbers. Nature 403: 843–845.

Pruett CL, Patten MA, Wolfe DH. 2009. Avoidance behavior by prairie grouse: Implications for development of wind energy. Conservation Biology 23: 1253–1259.

Rogers AL, Manwell JF, Wright S. 2006. Wind Turbine Acoustic Noise (amended). Renewable Energy Research Laboratory, Department of Mechanical and Industrial Engineering, University of Massachusetts at Amherst.

Saenz S, Walschburger T, Gonzalez JC, Leon J, McKenney B, Kiesecker J. 2013. A framework for implementing and valuing biodiversity offsets in Colombia: A landscape scale perspective. Sustainability 5: 4961–4987.

Sawyer H, Nielson RM, Lindzey F, McDonald LL. 2006. Winter habitat selection of mule deer before and during development of a natural gas field. Journal of Wildlife Management 70: 396–403.

Smallwood KS. 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Society Bulletin 37: 19–33.

Soeder DJ, Kappel WM. 2009. Water Resources and Natural Gas Production from the Marcellus Shale. US Geological Survey. Fact Sheet no. 2009-3032.

Trail PW. 2006. Avian mortality at oil pits in the United States: A review of the problem and efforts for its solution. Environmental Management 38: 532–544.

Winder VL, McNew LB, Gregory AJ, Hunt LM, Wisely SM, Sandercock BK. 2013. Effects of wind energy development on survival of female greater prairie-chickens. Journal of Applied Ecology 51: 395–405. doi:10.1111/1365-2664.12184

Yergin D. 2006. Ensuring energy security. Foreign Affairs 85: 69–82.

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