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Energy Development and Production in the Great Plains: Implications and Mitigation Opportunities

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ABSTRACT

Energy is an integral part of society. The major US energy sources of fossil fuels (coal, oil, natural gas); biofuels (ethanol); and wind are concentrated in grassland ecosystems of the Great Plains. As energy demand continues to increase, mounting pressures will be placed on North American grassland systems. In this review, we present the ecological effects of energy development and production on grassland systems. We then identify opportunities to mitigate these effects during the planning, construction, and production phases by using informed methodology and improved technology. Primary effects during energy development include small- and large-scale soil disturbance and vegetation removal as small patches of grasslands are used to host oil or gas wells, wind turbine pads, associated roadways, and pipelines or through the conversion of large grassland areas to biofuel croplands. Direct habitat loss or habitat fragmentation can affect wildlife directly through increased mortality or indirectly through reduction in habitat quantity and quality. During energy production, air and water quality can be affected through regular emissions or unplanned spills. Energy development can also affect the economy and health of local communities. During planning, energy development and production effects can be reduced by carefully considering effects on grasslands during siting and even by selecting different energy source types. During construction, effects on soil and plant systems can be minimized by eliminating weed populations before disturbance, salvaging and stockpiling topsoil for future revegetation, and harvesting native local seed for postsite restoration. During energy production operations, noise and road traffic reduction plans and atmospheric monitoring will enable more informed mitigation measures. Continued research on energy development effects and mitigation measures is necessary to establish best management practices beneficial to grassland health while providing needed energy for the United States.

Introduction

Multiple sources of energy including coal, oil, natural gas, and wind energy are concentrated in the grassland states of the United States. In 2015, only 12 of the 50 states produced more energy than they consumed. Seven of these states were located in the grassland region of the central United States (Table 1). Grassland states that are not net exporters of energy often have energy resources from the grassland region being transported through their boundaries on roadways, railways, and pipelines. For example, nearly 28% of the 1.8 million miles of oil and gas pipelines in the United States are located in the grassland region (see Table 1).

The tradeoff between energy production and conservation of lands within the grassland region leads to some difficult management choices. Identifying the ecological costs of energy production can help avoid and minimize environmental problems, as well as lead to the development of new technologies and approaches to aid in conservation. The potential effects of energy development on terrestrial and aquatic ecosystems and species have been reviewed by others (Erickson et al. 2005; Bayne et al. 2011; Northrup and Wittemeyer 2012; Brittingham et al. 2014; Souther et al. 2014; Shuster et al. 2015; Post van der Burg et al. 2017). We

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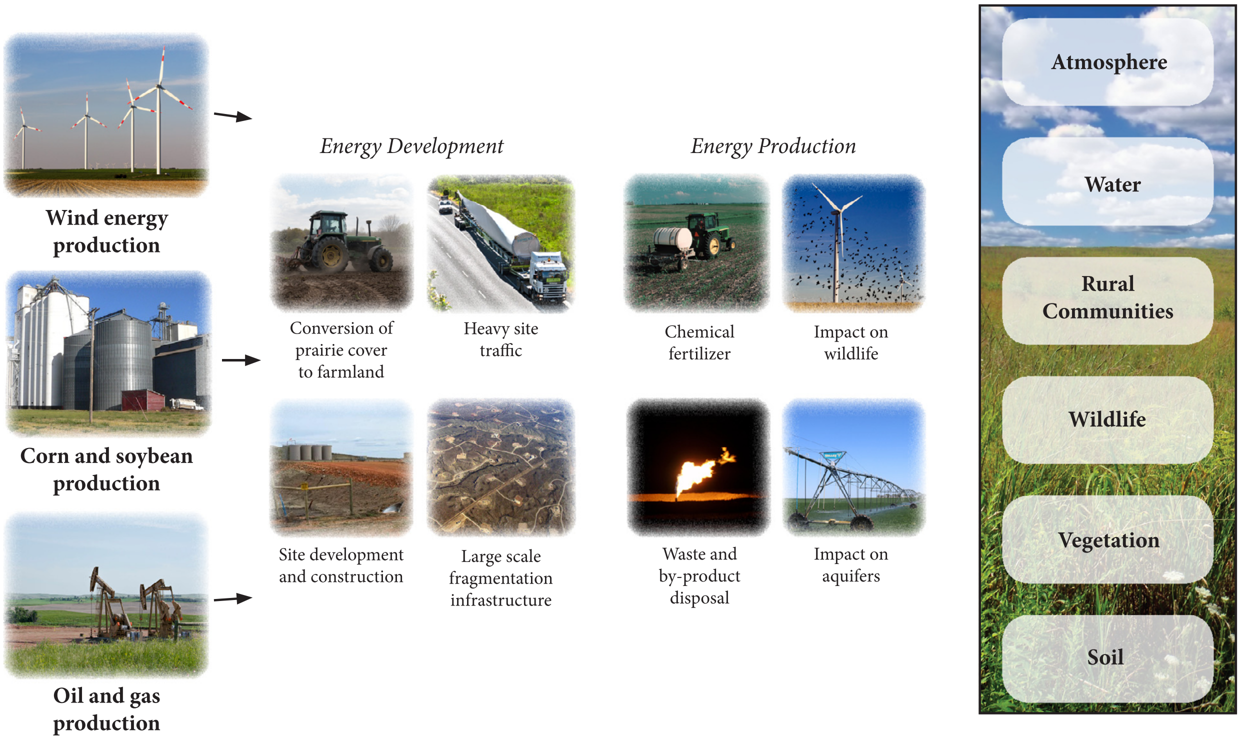

Fig. 1. Energy development and production can influence the environment in multiple ways. During development, land can be converted, fragmented, or disturbed. During production, the atmosphere, aquatic and terrestrial resources, and local communities can be affected.

set out to synthesize available information about how energy development and production affect grassland habitat (e.g., soil, water, air, vegetation, wildlife; Fig. 1) throughout the Great Plains. Through this synthesis we hope to identify opportunities to maintain grassland resiliency and restore grasslands following energy development.

Development of all energy sources is on the rise in the Great Plains. Some of the largest increases of oil and gas extraction in the past 10 yr have occurred in the Williston Basin in North Dakota and Montana and the Permian Basin in Texas and New Mexico (Fig. 2**).** Every yr since 2000, 50,000 new wells on average have been added throughout central North America with the majority being drilled on private land (Allred et al. 2015). In states like North Dakota, there were ~3 000 active wells in the yr 2000, which has increased to > 14 000 active wells at the beginning of 2018 (ND Oil and Gas Commission 2018).

As coal consumption has declined, development of natural gas and renewable energy sources has increased (Fig. 3). As of 2018, renewables in the United States make up 11% of total energy consumption with hydroelectric and wind energy each providing a quarter of the renewable supply (EIA 2018). Of the renewable energy technologies being deployed in the Great Plains, wind energy has seen the fastest growth over the past 2 decades (US DOE 2017; EIA 2018). The 15 Great Plains states with grasslands have > 42300 wind turbines with a combined 74221 MW of wind energy capacity, representing 76% of total US wind capacity, which could power ~7 million households (see Fig. 2, Hoen et al. 2018; AWEA 2019). Solar represented only 2% of total electricity generation in the United States in 2017, and Texas, which provides ~3% of the US solar capacity, is the only notable solar-producing state in the Great Plains (US DOE 2019). From 2006 to 2016, ethanol production in the United States increased from 4.9 billion gallons to 15.3 billion gallons with many biofuel crops being produced on converted grasslands (USDA-Economics Research Service, 2017).

Energy demand will place increasing pressure on the grasslands of the United States in future years. Because of the patchwork of land ownership that occurs throughout the Great Plains, energy extraction, production, transportation, and demand for water will affect lands of not only the property owner harvesting the energy but also those owned by surrounding neighbors who might have pipelines, electricity transmission and distribution lines, or truck traffic traversing their property. Additionally, energy processing power plants are located throughout the Great Plains, especially near large energy sources or near population centers (EIA 2018). Power plants, processing plants, and refineries can disrupt the landscape as energy is transported to and from their location and via emissions during on-site energy processing. Harvesting and processing energy can provide landowners with economic compensation for increased risk of oil or produced water spills and reduction of land in agricultural production and can enable landowners to subsidize their livestock or other operations.

Table 1
Energy production-to-consumption ratios and pipeline mileage for 10 grassland states. Production: Consumption ratios were calculated from 2015 data available from the Energy Information Administration of the United States. Pipeline mileage is presented as the % of total US oil and gas pipeline in the United States (data source: Pipeline Safety Trust 2013).

	CO	KS	MT	NE	NM	ND	OK	SD	TX	WY
Production-to- consumption ratio	2.2	0.8	2.8	0.5	4.0	3.0	2.4	0.6	1.4	17.3
% Total pipeline mileage	2.8	2.7	0.8	1.2	1.5	1.6	3.0	0.4	12.8	1.0

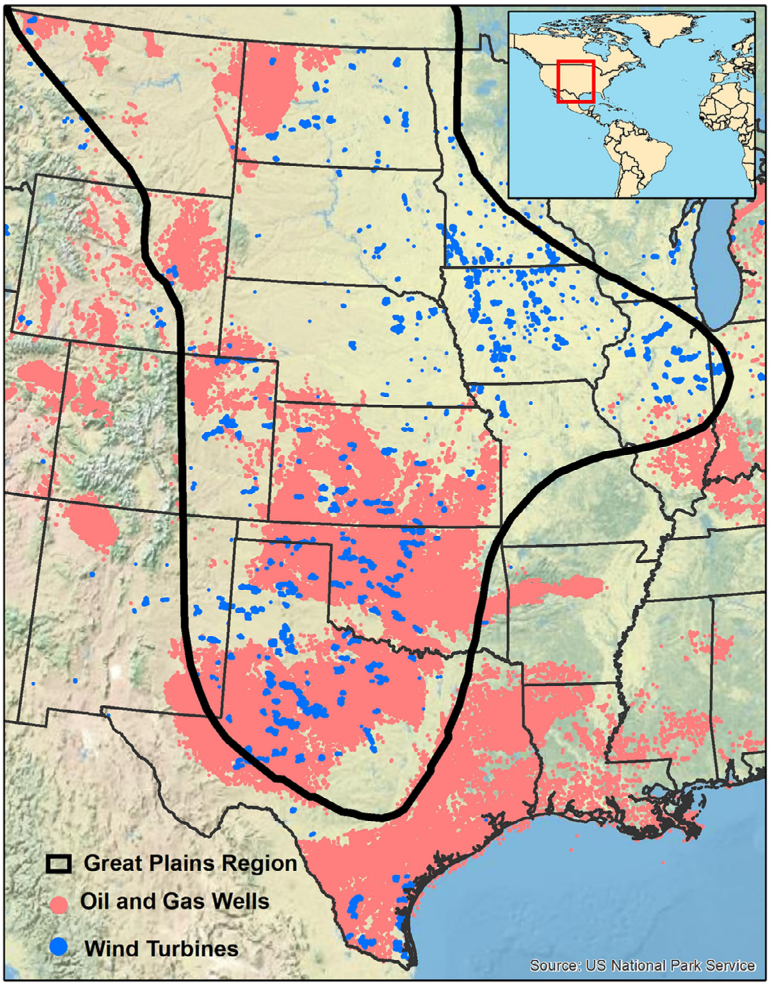

Fig. 2. Active oil and gas wells (shown in red) and wind turbines (shown in blue) in the Great Plains of the United States. Oil and gas development and production occurs throughout the Great Plains. The outline of the Great Plains region follows Lauenroth et al 1999. Data for all active oil and gas wells come from Enverus.com (downloaded January 10, 2020) for all states except Illinois. Illinois wells completed after January 1, 2000 were obtained from Illinois Clearinghouse (downloaded January 9, 2020). Wind turbine locations were obtained from the United States Wind Turbine database hosted by the USGS (downloaded January 7, 2020).

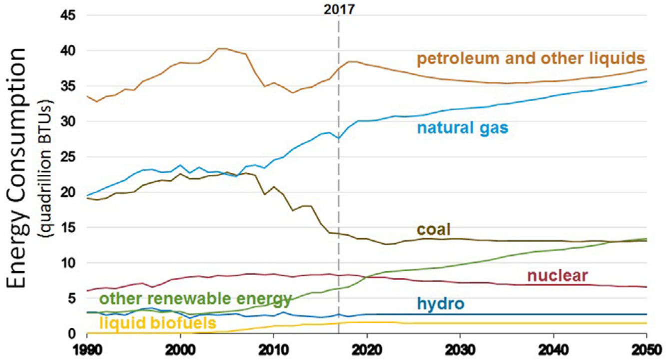

Fig. 3. Historical and projected energy consumption for the United States according to energy source (adapted from EIA 2018). The United States consumed 97 quadrillion British thermal units (~28 427 TWh) in 2017 (EIA 2018). Energy consumption encompasses industrial, commercial, transportation, and residential energy use.

To provide an overarching perspective on the effects of energy development and generation on grasslands and associated mitigation opportunities, we first provide overviews of four main ecological effects of energy development and production on natural resources. This overview is followed by mitigation opportunities that arise as one proceeds through the energy extraction cycle of energy planning, development and construction, and production. We identify knowledge gaps in ecological effects and mitigation opportunities and look forward to future research that can further assist with minimizing the effects of energy development. Our focus is on local and regional effects on grasslands as other literature covers the global effects of energy usage (e.g., climate change). We also focus on grassland habitat and only briefly mention the effects of energy development on rural communities.

Ecological effects

Land Conversion and Fragmentation

The first, and most observable, effect of energy development in grasslands is direct habitat loss. Every energy source requires some amount of land to be temporarily or permanently converted to accommodate energy infrastructure pads, power stations, transmission lines, biofuel crops, or new service roads. A modern wind turbine requires ≈1.2 ha of land, including the turbine pad and access roads (Arnett et al. 2007; Diffendorfer et al. 2019). During oil and gas extraction, initial well sites require several hectares to accommodate drilling and hydraulic fracturing equipment and supplies and settling and mud pits (Kroepsch 2018). After drilling, oil

Table 2
Land affected during energy harvest, economic costs of power plants, and power plant water use according to various energy sources. The United States consumes ~28 427 TWh annually.

Energy source	Land used (km^2/TWh)[1]	Life cycle costs of a power plant ($/MWh)[2]	Power plant water consumption (L/MWh)[3]
Nuclear	0.1	92.6	1 700
Oil & natural gas	3-8	49.0-74.9 (natural gas)	520-850 (natural gas)
Coal	8	119.1-130.1	1 400-1 900
Solar	15-19	63.2-165.1	10
Wind	127	85.1-98.7	4
Biofuels	236-565 for liquid fuel, 810 for electricity	95.3	2 100

[1] Indicates land use data including both the production of electricity and liquid fuel from the energy sources, whereas power plant values are focused only on electricity generation. Land use values are from Trainor et al. 2016. The land use includes the direct footprint of energy harvesting infrastructure, as well as spacing requirements of infrastructure (such as wind turbines needing to be spaced a certain distance from one another). The land use value does not account for multiple-yr harvest from the same piece of land. Most energy sources can be continually harvested from the same piece of land for multiple years, but the length of each source differs (e.g., biofuels can be harvested from the same piece of land longer (~100 yr) than oil and gas (~40 yr).

[2] Life cycle costs of power plants are derived from simple averages for total system levelized costs (EIA 2018). Ranges of life cycle costs occur depending on the technology used (e.g., carbon capture and sequestration processes).

[3] Power plant water consumption per electricity-generated values are from Jackson et al. (2014). Inclusion of irrigation in the power plant water use values of biofuels would raise the water needed to 16000 L/MWh.

and gas well pad sizes can be greatly reduced during production, enabling site restoration to begin. Oil and gas well pad sizes can range from 1.6 ha to 2.8 ha depending on how many wells are colocated on one pad (END 2020). Pipelines and electrical transmission lines can require more land than the well pad or production facility (Slonecker et al. 2012). Great Plains surface coal mines, which primarily occur in Wyoming (15 mines) and North Dakota (5 mines), can create large areas of soil disturbance up to several hundred hectares per mine during coal extraction (EIA 2019). However, the most recent dramatic land use conversion is the conversion of grasslands to croplands in support of biofuel production, which was encouraged via federal subsidies. From 2006 to 2011, 526000 ha of land were converted from grasslands in North Dakota, South Dakota, Nebraska, Minnesota, and Iowa into cropland for corn and soybean production (Wright and Wimberly 2013; Morefield et al. 2016; Wimberly et al. 2017).

When considering the amount of land needed to produce one TerraWatt-hour (TWh) of electricity (i.e., land use), nuclear power is the most land efficient energy producer (Table 2). Nonrenewable energy sources such as oil, gas, and coal require less land per unit energy than renewable energy sources (see Table 2). In order to produce comparable energy as fossil fuels, wind power encompasses 15−40 times more land, and biofuels and biomass use 25−267 times more land. However, renewable energy production, by definition, can continue on the same land base once developed, whereas fossil fuel extraction energy must shift to sustain production. Taking into account the ability for renewable energy to “reuse” land, it would take wind power decades and biofuels centuries to reach land use equivalency with fossil fuels (Trainor et al. 2016).

Land-use change directly reduces habitat for native plant and animal species (e.g., biofuel crop production reduces nesting habitat for grassland bird species and managed honeybee colonies in the Northern Great Plains; Otto et al. 2016; Otto et al. 2018). Small amounts of land conversion throughout a region can add up to large regional effects. For example, oil and gas development during 2000 to 2012 used 3 million ha and reduced forage production, as measured by dry biomass, by 10 Tg across central North America, which is ≈5 million animal unit months, greater than half of the annual grazing on Bureau of Land Management lands (Allred et al. 2015).

In addition to losing native or naturalized habitat to energy use, the distribution of energy pads and associated infrastructure can lead to habitat fragmentation as land not used for energy development is divided into smaller, more isolated patches. Energy production often results in “energy sprawl,” or large extents of crop fields, roads, power lines, pipelines, substations, and pads for oil and gas wells, wind turbines, and solar panels (Trainor et al. 2016). Land fragmentation can affect plant seed dispersal and animal movements, making it difficult for individual survival and maintenance of population viability and genetic diversity. Fragmentation can also introduce edge effects that can influence large portions of the landscape, often leading to increased spread of invasive species and alterations of predator communities (Evangelista et al. 2011; Preston 2015; Preston and Kim 2016). Changes in the presence and structure of grassland vegetation will undoubtedly have positive and negative effects on multiple wildlife species. Non-native species can alter habitat quality and, combined with direct habitat removal, be especially disruptive for edge and area sensitive species such as terrestrial invertebrates (i.e., butterflies; Skórka et al. 2015) or cause birds (e.g., Carpenter et al. 2010; Gilbert and Chalfoun 2011; Hamilton et al. 2011; Ludlow et al. 2015; Thompson et al. 2015), mammals (Sawyer et al. 2006; Kolowski and Alonso 2010; Rabanal et al. 2010) and herpetofauna (Moseley et al. 2009) to avoid areas near developments. Many of these studies have focused on observed changes in densities or abundances near developments, but there is some evidence that disturbances from energy extraction may alter reproduction and recruitment (Van Wilgenburg et al. 2013; Hethcoat and Chalfoun 2015) or animal distributions (Sawyer et al. 2006).

Many of these studies focused on wildlife avoidance of focal sites where extraction is taking place (i.e., well pads). However, in order to access these sites, developers must construct miles of roads. Vehicular traffic has the potential to harm or kill terrestrial and aquatic species, modify animal behavior, alter habitats, contaminate water, and spread exotic species (Sutter et al. 2000; Trombulak and Frissell 2000; Evangalista et al. 2011; Hamilton et al. 2011). Landscape patterns of remaining habitat could modify the effects of roads. For species that can move from patch to patch, the relative amount and quality of habitat near a road may increase or decrease species movement, which increases mortality near roads, especially for invertebrates (Skórka et al. 2013; Skórka et al. 2015) and amphibians (Carr et al. 2001; Hels and Buchwald 2001; Cosentino et al. 2014). Much of the work with birds and mammals focuses on patterns of road avoidance, as opposed to more direct effects such as mortality (Benitez-Lopez et al. 2010; Garrah et al. 2015; Ludlow et al. 2015; D’Amico et al. 2016). Results vary by species with some showing negative, neutral, or positive effects near roads (Zelenak and Rotella 1997; Ludlow et al. 2015; Wallace et al. 2016). For other species, the effects of roads appear to vary by time of day (Dzialak et al. 2011; Northrup et al. 2015). Roads may also provide opportunities for illegal hunting or increased harvest efficiency of big game species (e.g., Thibault and Blaney 2003; Dorning et al. 2017).

Fragmentation effects can occur in both renewable and nonrenewable energy developments. Wind energy facilities placed in native grasslands and grass pastures contribute to land fragmentation and habitat loss, leading to avoidance, displacement, and altered reproductive success of grassland birds (Leddy et al. 1999; Loesch et al. 2013; McNew et al. 2014; Shaffer and Buhl 2016; Harrison et al. 2017). Certain bird species, including the lesser prairie chicken *(Tympanuchus pallidicinctus)* and the greater prairie chicken *(T. cupido pinnatus)* avoided utility poles or power lines by at least 100 m at two study sites in Oklahoma (Pruett et al. 2009). Lesser prairie chickens are also sensitive to disturbance from roads and other infrastructure (Pruett et al. 2009; Plumb et al. 2019). A series of studies focused on the greater prairie chicken in Kansas suggest that both male and female greater prairie chickens alter their behavior when turbines are located within 8 km of leks (Winder et al. 2014a, 2014b, 2015). Ducks, greater sage-grouse, and sandhill cranes have experienced declines in breeding or altered distributions due to wind development (Loesch et al. 2013; Le Beau et al. 2014; Pearse et al. 2016).

Soil Disturbance and vegetation removal

All physical disturbances of soil and vegetation increase the risk of soil erosion depending on precipitation, vegetative cover, slope, and soil texture (Renard et al. 1997). Intact grassland vegetation tends to lower the erosion rate while areas devoid of vegetation can experience rapid soil loss and gullying (Smith et al. 1984). Management efforts that reduce the area of bare, exposed soils and soil disturbances reduce soil erosion loss (Smith et al. 1984). When soils are exposed or disturbed, rapid site treatment can further minimize soil loss.

During construction of energy projects, unpaved roads are often the greatest source of soil erosion in areas of energy development (Stednick et al. 2010). Erosion rates can decline on unpaved roads as surfaces harden and vegetation develops along roadsides or with the use of gravel. However, erosion rates from unpaved roads can increase with increasing traffic and road maintenance activities (Rehder and Stednick 2006). Because soil erosion can lead to water quality degradation, which is regulated by the Clean Water Act, best management practices (BMPs) have been developed to avoid and/or manage erosion. These BMPs are beyond the scope of this review, but see Tyner et al. (2011).

Soil disturbance can alter soil nutrient cycling. Plants continuously remove available nutrient elements from soil solutions, and nutrients, such as mineralized forms of nitrogen, can build up in the soil when plants are removed. Nutrient levels can be further elevated by increased microbial decomposition of organic matter due to greater moisture availability and higher soil temperatures where plant canopies are lacking. Such conditions are prime niches for early successional plant species that are adapted to such conditions and readily colonize disturbed soils (Perry et al. 2010). However, many early successional plant species that dominate Great Plains ecosystems are non-native species. A common mistake of managing disturbed soils is to exacerbate the problem by applying fertilizers, which leads to further dominance and spread of weedy exotic species (Paschke et al. 2000).

The loss of a diverse native plant community can have cascading effects on wildlife, insects, and belowground soil biological communities. Several studies have found that recovery of vegetation after oil and gas development in the Great Plains can require many decades (Nasen et al. 2011) and recovery may (Baer et al. 2002) or may not (Rottler et al. 2018) be aided by restoration treatments. Vegetation in areas surrounding directly affected sites can also be affected by fugitive dust, altered site hydrology, and altered behaviors of wildlife (Nasen et al. 2011).

Infrastructure presence

Ecosystems are inherently interconnected. Therefore, effects at one trophic level or in one part of the community network can affect other trophic levels or influence other parts of the community via existing network connections. New roads and infrastructure associated with energy facilities can create changes to predator activity, further contributing to effects on resident wildlife (Hethcoat and Chalfoun 2015). Increased infrastructure is thought to offer increased perches for avian predators, which could lead to declines of small mammals or other birds. However, the expected negative response is not always observed. For example, Burr et al. (2017) examined the nest predation of sharptail grouse *(T. phasianellus)* at two locations in Mountrail County near the Bakken oil field of North Dakota. Nest predation was lower at the site with greater oil and gas development likely due to predators avoiding the site. Although the effects of infrastructure are primarily related to wildlife, the plant community can experience secondary effects such as reduced seed dispersal, increased pollination, or increased spread of invasive or non-native grasses (Francis et al. 2012).

Sound and light pollution during energy production may also exacerbate the negative effects of habitat fragmentation (Gaston et al. 2014). Disruptions from industrial noise can affect the ability of various species to locate prey, find mates, and avoid predators (Francis and Barber 2013). Noise has been shown to lower bird abundance and breeding activity (Habib et al. 2007; Francis and Barber 2013; Kociolek et al. 2011; Blickley et al. 2012), lower arthropod abundance (Bunkley et al., 2017), disrupt reproductive behavior in amphibians (Sun and Narins 2005; Bee and Swanson 2007), and perhaps even result in hearing loss or mortality of aquatic species like fish (Popper et al. 2005). Such effects may be more pronounced in grasslands because sound can travel further when unobstructed (Forman et al. 2002; Bayne and Dale 2011). Lighting associated with extraction sites can also affect bird behavior and survival (De Molenaar et al. 2006; Gauthreaux and Belser 2006; Kociolek et al. 2011). Gas flares at oil and gas developments can attract birds or other species, resulting in increased mortality from direct contact with flames (Wiese et al. 2001).

Direct effects of wind energy development include bird and bat mortality from collisions with operating wind turbine blades (Arnett et al. 2007; Loss et al. 2013; Zimmerling et al. 2013; Smith and Dwyer 2016). In the Great Plains states, many species of birds (songbirds, grassland birds, upland gamebirds, birds of prey, waterfowl, wading birds, shorebirds) and bats have been found dead underneath wind turbines (Arnett et al. 2008; Fargione et al. 2012; Gaff et al. 2016). Bird and bat mortalities are highest during fall migration, with a second, lower peak during spring migration (Thompson Beston et al. 2017). This is especially a concern for protected migratory birds (US Department of Justice 2013).

Release of byproducts and use of local water

Terrestrial/aquatic systems

Waste products from energy development and production, which are stored on-site or transported via roads, have the potential to negatively affect water resources and soils across the Great Plains. Of particular concern are the numerous toxic chemicals used in hydraulic fracturing (also known as *unconventional drilling*) for oil and gas development (Boehm et al. 2013; Gordalla et al. 2013; Auers et al. 2014). Additionally, water needs for oil and gas development could contribute to competition for scarce water resources (Vengosh et al. 2014).

Highly saline coproduced water has been highlighted as a potentially toxic and large-volume byproduct of unconventional oil and gas extraction (Sirivedhin and Dallbauman 2004; Fakhru'l-Razi et al. 2009). Coproduced waters, or "brines," contain a wide variety of compounds including oils, formation minerals, chemical compounds, production solids, and dissolved gases (see Fakhru'l-Razi et al. 2009 and references therein for more description of compounds) and are suggested to be one of the leading causes of contamination associated with tight shale plays (Kharaka and Otton 2003; Gleason and Tangen 2014). Often, the concentration of an indicator in soil or water is used to identify contamination; however, as pointed out by Post van der Burg and Tangen (2015), many natural systems, like wetlands, have a wide range of natural variability in chloride, which may make those indicators difficult to use (but see Cozzarelli et al. 2017). In the Williston Basin, subsurface migration of brines from disposal pits have been implicated in wetland and shallow groundwater contamination (Thamke and Craigg 1997; Preston et al. 2014). Storage of drilling and pumping wastes in pits and other facilities also poses risks to wildlife, which could become trapped or submerged in toxic water (Trail 2006; Ramirez 2010). In many states disposal pits are no longer legal (e.g., North Dakota Administrative Code 43-02-03-19.3; Administrative Rules of Montana 36.22.1207; Administrative Rules of South Dakota 74:12:04:09), but legacy pits may continue to pose a problem unless properly remediated. Surface discharges from accidents or leakage account for ≈5% of the produced water volume associated with hydraulic fracturing (Sirivedhin and Dallbauman 2004) and are likely the largest source of produced water contamination (Thamke and Craigg 1997). While toxic spills are a major focus, dust suppressants, soil stabilizers, and ice melters applied to roads can also end up in aquatic ecosystems. Soil disturbances and vegetation are also likely to increase sediment deposition or pollution in wetlands and streams (McBroom et al. 2012; Brittingham et al. 2014; Entrekin et al. 2015).

Alterations of hydrology could also affect wetland water quantity. For example, hydraulic fracturing requires large amounts of water (e.g., between 28 and 50 million gallons per well; Scanlon et al. 2014; Shonkoff et al. 2014) and developers may draw that water from nearby aquatic systems. Withdrawals have the potential to lower water levels in wetlands, which could impact ranching and wildlife (e.g., Mushet 2010). Conflicts over water, among users including agriculture, urban centers, and the energy sector, may affect water rights and interstate water compacts. Wind and solar power plants use less water than power plants for all other energy types (Table 2). Freshwater withdrawals for thermoelectric power and irrigation remained the two largest users of freshwater during 2010, at about 38% each (Maupin et al. 2014).

Manufacture and disposal of solar and wind energy infrastructure may yield potential environmental and human health issues in grassland states. Both solar panels and wind turbines use mined rare earth elements. For example, sludge from manufacture and used solar panels contain cadmium and lead (Xu et al. 2018). Manufacture and waste disposal also use fossil fuels, and combustion produces carbon dioxide, methane, nitrous oxides, air particles, and sulfur dioxide (50−105 gCO_2eq/kWh; Nugent and Sovacool 2014). Complete decommissioning and recycling of renewable energy waste, including solar panels and mixed material electronics, may not occur due to its high cost (Davidsson et al. 2012) and lead to negative effects, where these materials are placed at the end of their life cycle.

Atmosphere

In the Great Plains, oil and gas development releases several regulated air pollutants (Allen et al. 2013; Field et al. 2014; Peischl et al. 2016). Air pollutants that can harm sensitive resources include ground-level ozone, fine particles, sulfate, nitrate, ammonia, and airborne toxics. Emissions come from a large number of small sources, typically with a small number of wells being responsible for a large percentage of emissions (Rella et al. 2015; Lyon et al. 2016). Many studies have focused on methane (Howarth et al. 2011; Allen et al. 2013; Brandt et al. 2014) because it is a powerful greenhouse gas and atmospheric methane concentrations have increased globally in the past decade (Nisbet et al. 2014). Although the causes for this increase are not completely understood, there have been increases in US methane emissions, particularly in the central United States (Turner et al. 2016), and emissions related to fossil fuel extraction are thought to play a role in global methane trends (Bader et al. 2017). Along with methane, other pollutants such as volatile organic compounds (VOCs), including air toxics, can be released (Petron et al. 2012; Halliday et al. 2016). VOCs are gas-phase organic compounds that can have natural or anthropogenic sources, some of which can negatively impact human health and serve as precursors for ground-level ozone and secondary organic aerosol formation. These emissions result from a variety of processes and include venting, flaring, equipment leaks, liquids unloading, and pneumatic devices, which use gas pressure to control the operation of mechanical devices such as valves (Allen 2016). Coal produces more pollutants than natural gas, such as about 820 gCO_2eq/kWh (grams of carbon dioxide equivalent per kilowatt-hour of electricity) compared with 490 gCO_2eq/kWh (Nugent and Sovacool 2014; Schlömer et al. 2014). However, incorporation of the extent of fugitive emissions plays a critical role in determining whether natural gas provides less greenhouse gas emissions when compared with coal (Howarth et al. 2011). These issues are particularly significant in the Northern Great Plains, where it is estimated that methane emissions from the Bakken correspond to leakages of nearly a tenth of energy content (Schneising et al. 2014). There are also emissions from the equipment and trucking events needed for oil and gas development (Bar-Ilan et al. 2011), including VOCs, NO_x, black carbon (BC or soot), particulate matter, and SO_2. In the Northern Great Plains, flaring is also a major pollutant source, releasing carbon monoxide (CO), NO_x, and BC (Schwarz et al. 2015; Weyant et al. 2016). Flaring often occurs to convert dangerous gases into more stable byproducts or to remove excess natural gas due to the inability to get the product to market (e.g., not enough pipeline capacity).

Crop biofuels (e.g., corn-based ethanol) have great land, water, fertilizer, and soil costs and result in a chain of fossil fuel use and emissions (Hill et al. 2009), leading to the conclusion that crop biofuels have limited potential to reduce emissions compared with oil. Wind turbine construction produces emissions and is the main (80%) phase of emissions during the life cycle of wind energy development and harvest (Lago et al. 2009). Although wind turbines do not emit greenhouse gases, they may cause local heating and affect wind patterns (Vautard et al. 2014). In the west central Texas region, daytime temperatures increased by 0.724°C over a decade and evening temperatures increased by a greater amount due to a farm with 2358 wind turbines (Zhou et al. 2012). Similar results at a southern California windfarm corroborated this finding (Tabassum-Abbasi et al. 2014).

Nitrogen and sulfur pollution can deposit directly onto soil and plant surfaces (dry deposition) or can be deposited by rain, snow, and fog (wet deposition) threatening sensitive aquatic and terrestrial resources. As noted, energy development is a major source of $NOx_,$ and modeling results suggest that oil and gas activities have led to increases in nitrogen deposition throughout the Great Plains (Thompson Shepherd et al. 2017). Potential effects of excess nitrogen inputs include impacts on water quality and nutrient cycling, nitrogen enrichment in soils and plants, eutrophication of lakes, reduced diversity, altered plant community composition, increases in invasive species, changes in fire frequency, and impacts on drought, frost, and pest tolerance (Fenn et al. 2003; Pardo et al. 2011a). Field studies investigating nitrogen deposition in the Great Plains show that their characteristic grasslands are expected to be sensitive to nitrogen inputs (Clark 2011; Simkin et al. 2016). Critical loads are thresholds at which we expect to see an ecosystem response and are useful tools for translating ecosystem effects into specific air quality targets. Critical loads have been estimated at 10–25 kg N $ha^{-1}yr^{-1}$ for mixed and short-grass prairie, and 5–15 kg N $ha^{-1}yr^{-1}$ for tallgrass prairie (Clark 2011), although slightly lower critical loads have been suggested for specific communities (Symstad et al. 2015). For comparison, wet nitrogen deposition ranges from 1 to 7 kg N $ha^{-1}yr^{-1}$ in the Great Plains, increasing from west to east; total N deposition is estimated to be twice those values (Clark 2011). Critical load estimates are based on observed shifts in key indicators due to the addition of nitrogen. For example, Jorgensen et al. (2005) found that nitrogen addition to a mixed-grass prairie in Oklahoma resulted in increased soil nitrate and total plant biomass. Wedin and Tilman (1996) reported that nitrogen addition on Minnesota grasslands increased soil nitrate, decreased species richness, increased productivity, and increased invasive species. Symstad et al. (2015) showed that the addition of nitrogen impacted biomass production, grass tissue nitrogen concentration, and non-native species in the northern Great Plains. Other studies have also explored the impacts of nitrogen addition (see review in Clark et al. 2011), and Pardo et al. (2011b) have suggested that the nitrogen critical load for herbaceous species may be exceeded across much of the Great Plains.

Ground-level ozone forms when VOCs and NO_x react in the presence of sunlight affecting human and plant health. Plant responses to elevated ozone levels include reduced photosynthesis and productivity (Bassin et al. 2007; Ainsworth et al. 2012), leading to visible injury (stippling and necrosis), reduced growth rates, and decreased survival (Lefohn et al. 1997). Ozone susceptibility varies by species, climate, and soil moisture availability. While there are few studies in the Great Plains, a number of plant species in the northern Great Plains are known to be sensitive to ground-level ozone (Sullivan 2016). However, in a study assessing the risk of ozone injury in National Park units across the United States, Kohut (2007) determined the risk to be low in parks in the Great Plains, due in part to relatively dry soil conditions in summer. Ozone effects are often magnified from extended exposure during the growing season. The W126 metric calculates cumulative ozone exposure between spring and fall, giving higher weighting to the more critical times of the season (Lefohn et al. 1988). Nationwide, W126 is largely influenced by anthropogenic NO_x emissions (Lapina et al. 2014) creating atmospheric ozone, and significant increasing trends of NO_2 have been observed in the Bakken region (McLinden et al. 2016) of the northern Great Plains. Oil and gas extraction activities in this region have also been shown to drive higher ambient concentrations of VOCs and NO_x (Prenni et al. 2016), and modeling results suggest that these emissions can affect ozone formation in regions downwind of the development (Kort et al. 2016; Thompson et al. 2017). Similarly, emissions from shale gas regions are thought to contribute to high ozone days in northern Texas (Ahmadi and John 2015). Biofuels have similar, but reduced, emissions of ozone and fine particulates relative to gasoline, both at ethanol refineries (Jones 2010) and during combustion in vehicles (Tessum et al. 2014).

Mercury and certain VOCs are the main toxic pollutants found in the atmosphere that are associated with energy production and use. A major source of mercury is coal-fired power plants emissions. While large reductions in SO_2 and NO_x emissions from coal-fired power plants (Fig. 4) have occurred with associated decreases in mercury emissions (Zhang 2016), significant increases in wet deposited mercury have been reported for the Great Plains from 2007 to 2013 (Weiss-Penzias et al. 2016). Once deposited, inorganic mercury can be converted to methylmercury, which can bioaccumulate in the food chain, causing behavioral, neurologic, and reproductive effects in fish, birds, and wildlife. In a study of 21 national parks across the western United States, mercury concentrations in 35% of the fish sampled were above a benchmark for risk to highly sensitive avian consumers (Eagles-Smith et al. 2014). In 2011, all 50 states had mercury advisories in effect, covering ≈16.4 million lake acres and 1.1 million river miles (EPA 2011).

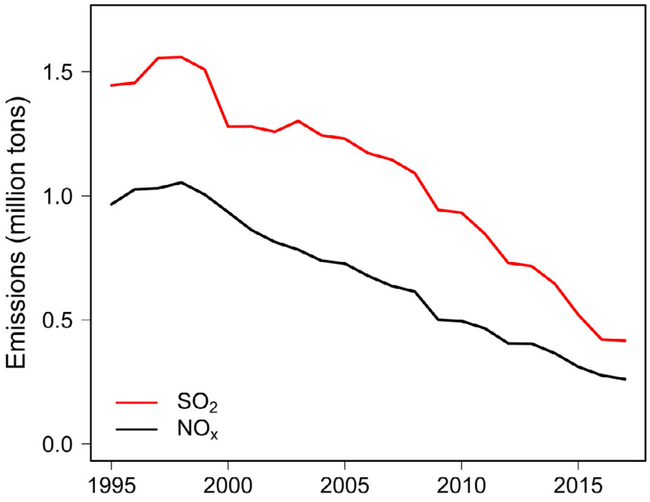

Fig. 4. SO_2 and NO_x emissions from power plants in the Great Plains of the United States. Large reductions in emissions occurred over the past 20 yr, all while increasing energy output (not shown). These reductions are likely also tied to an increase in renewable energy sources such as wind and solar (Millstein et al. 2017), as well as an increase in the use of natural gas (Allen 2016). Data are from EPA Air Markets Program, available at: https://ampd.epa.gov/ampd/ (Downloaded February 13, 2018).

Toxic organic compounds including benzene, toluene, ethylbenzene, and xylene (BTEX) come from fuel evaporation and are emitted during oil and gas extraction activities. Enhanced concentrations of BTEX compounds have been observed in several oil and gas basins throughout the Great Plains (Halliday et al. 2016; Koss et al. 2017). Hydrogen sulfide (H_2S) is another toxic air molecule that can be emitted from oil and gas sources. H_2S is corrosive to equipment and harmful to human health, even causing death at high exposures (Goodwin et al. 2015). Although hydrogen sulfide is typically removed before commercial use, significant enhancements of H_2S have been observed in the Permian Basin in Texas (Koss et al. 2017).

Fine particles in the air can cause lung irritation and contribute to dry deposition of nitrogen and sulfur species. At high concentrations fine particles create a visible haze, limiting sightlines, colors, forms, and textures of a scenic vista. These particles can result from direct emissions or chemical reactions of precursor species such as SO_2, VOCs, and NO_x. Energy development sources include fugitive dust from mobile sources (Bar-Ilan et al. 2011), elemental carbon from flaring and diesel emissions (Schwarz et al. 2015; Weyant et al. 2016), and soil and mineral dusts from surface coal mining (Kurth et al. 2015). Visibility monitoring data from the IMPROVE network (http://vista.cira.colostate.edu/improve/) suggest that oil and gas development in the Bakken region has clearly affected visibility. Hand et al. (2014) showed that haze levels are not decreasing on the worst haze days and that nitrate and sulfate concentrations have increased in winter (Hand et al. 2012). Haze episodes were shown to be dominated by ammonium nitrate across the region (Evanoski-Cole et al. 2017). This is counter to national trends, where steady improvements in visibility have been observed due to mitigation strategies aimed at achieving regulatory goals spelled out in the Environmental Protection Agency's (EPA's) Regional Haze Rule (RHR). Specifically, the RHR calls for reasonable progress toward natural visibility conditions for the 20% haziest conditions in all Class I areas, including Theodore Roosevelt National Park in the Bakken region.

Mitigation opportunities

During the energy planning phase

Opportunity—Type of Energy Development

Each energy source has potential ecological effects and associated opportunities to reduce or mitigate their effect on the environment. Fossil fuels and biofuels are a reliable and transportable form of energy but have high greenhouse gas emissions. Nuclear energy has low greenhouse gas emissions but requires greater economic investment costs and can have siting (e.g., water availability due to high demand of water for cooling) and waste disposal challenges. The intermittent nature of energy production from wind and solar energy has been a challenge for balancing the power demands on the power grid. Nonrenewable energy supplements are often required to meet power demands. Because ecological impacts and benefits differ by energy type, local, state, and national authorities and regulators can tailor their energy development policies, particularly as energy demand is predicted to increase roughly 30% by 2050 (EIA 2018).

Energy development planning and authorization occur at different levels of government depending on land ownership. Although states have primary oversight and enforcement of relevant laws, energy development authorization typically occurs at the state level for private lands and federal level for public lands. The public has the opportunity to provide comment on development proposals, but local planners may have limited flexibility in shaping oil and gas development at the regional level. Nonetheless, local control of terms and conditions provides options to avoid, reduce, and mitigate consequences of energy development. Not all costs and benefits are summarized in standard energy costs (Epstein et al. 2011; OMB 2017). Some loss of ecological services in rangelands, such as forage for cattle, can be valued in currency, but other ecosystem services are difficult to quantify, including protection of wildlife, watersheds, ecological processes, recreation, scenery, potential cultural resources, ties to the land, and quality of life.

Opportunity—siting of energy development

Energy development effects on soils, vegetation, and wildlife can be minimized when conservation-planning and comprehensive site assessments are incorporated as part of the energy development planning process with the goal of locating development in areas that are of relatively low biological value. Areas containing sensitive plant species or communities, or plant species and communities of concern, are usually avoided in the permitting process. Minimizing effects on sensitive and endangered species can require additional planning and mitigation (e.g., Khalil 2018). Risk assessments can be developed for areas with oil and gas activity to focus monitoring efforts to minimize effects on water resources (Preston and Chesley-Preston 2015). Similarly, wildlife habitat modeling efforts that identify suitable habitats for grassland birds and raptors can help identify areas of high risk to wildlife susceptible to renewable energy development (Miller et al. 2014; Shaffer, Loesch and Buhl 2019). Critical wildlife habitat and migration corridors can be identified to inform site placement before development with a focus on site-specific information. For example, the response of mule deer to oil and gas development has been examined in the Bakken in North Dakota, Pinedale in Wyoming, and Piceance Basin in northwestern Colorado. In all locations, active drilling elicited the strongest avoidance response by mule deer. Avoidance of producing wells was 2.7 km in Wyoming, 600 m in Colorado, and little to none in North Dakota (Northrup et al. 2015; Kolar et al. 2017; Sawyer et al. 2017). These differences are likely due to differences in topography. Mitigating potential effects on migratory wildlife and their habitats include removing barriers to movement, especially geographic bottlenecks caused by human activities constraining movement in conjunction with existing topography, improving habitat through invasive species removal, and the Conservation Reserve Program (CRP), which restores cropland back to grassland. Additional approaches include concentrating development into smaller areas (Ludlow et al. 2015; Thompson et al. 2015, Preston and Kim 2016) and targeting development to already disturbed sites (Moran et al. 2015).

Ecological effects of energy development can also be reduced when projects are colocated with developed or working lands. Well- or turbine-pad spacing can limit or concentrate the amount of land-use conversion enabling some other land uses, such as crop production or grazing, to continue. For example, grazing and crop production can occur at oil and gas developments and wind turbine facilities. However, energy operations could introduce hazards, such as increased H_2S (see earlier discussion) or ice chunks developed overnight flying off turbines in the daytime, or benefits, such as increased shade. Drilling technology advances have increased the horizontal reach of shale gas wells to 1.6–3.2 km^2 (Butler et al. 2018) enabling one well-pad to host multiple wells, thereby reducing the project's footprint (Preston and Kim 2016). New wind turbines are significantly larger than older ones and generate more power per turbine, allowing facilities to install fewer turbines, spaced farther apart. Wind and solar energy can be sited on areas already disturbed by energy development or agriculture (Shaffer and Buhl 2016; Thompson et al. 2017; Davis et al. 2018) or on contaminated lands, landfills, and mine sites (see EPA's RE-Powering America's Land Initiative). Solar panels can be placed on existing structures without creating an added footprint. While efforts to plan development and mitigate ecological effects are possible and can provide certain efficiencies, energy project sites primarily occur at locations where a willing landowner can provide access to an available energy resource.

Years of wildlife fatality monitoring at wind facilities suggest that the location of wind infrastructure can influence bird collision mortality (Pagel et al. 2013). Advances in research on bird flight behavior, migration, and habitat use can provide resource managers with more sophisticated risk models and maps showing areas that may pose an elevated risk to bird species of conservation concern (e.g., Craig et al. 2018; Shaffer, Roth and Mushet 2019). New Global Positioning System–based telemetry that tracks bird flight altitude and movement at frequent time intervals (minutes) can be used to inform wind turbine siting decisions (Katzner et al. 2012; Wulff et al. 2016). Bird flight behavior of golden eagles and other raptors can be used to identify locations and turbine maximum heights that minimize overlap with airspace used by protected or listed species (Poessel et al. 2018; Duerr et al. 2019), although this type of research in the Great Plains is still limited. In the individual project planning phase, authorities and resource managers can evaluate bird collision risk at the proposed project site (New et al. 2015).

Looking forward—energy planning research needs

Most recommendations for mitigating wildlife and habitat effects in the Great Plains are currently directed at individual developments. Effects can accumulate across multiple energy developments and various land uses, such as agriculture and energy development. Project siting of both nonrenewable and renewable energy sources could be examined at larger scales to help plan out development over larger areas in order to leave wildlife corridors intact and prevent haphazard developmental patterns. Examining the collective impact of all energy sources can assist planners by providing a landscape perspective on energy footprints and emissions (Davis et al. 2018; McClung et al. 2019). As pointed out in Post van der Burg et al. (2017), decision analytic tools may prove useful in managing trade-offs between energy development, habitat preservation, and societal values under uncertainty about the future (e.g., Schneider et al. 2003; Smith et al. 2012). These tools can also aid in designing habitat reserves around energy development regions on the landscape (Schneider et al. 2011).

Cost-benefit analyses of energy development as part of the planning process can benefit rural communities during the planning stages. Energy development can bring local and regional societal benefits including local energy to drive down prices of electricity and transportation, job creation in rural localities, and new sources of income for landowners. For example, the American Wind Energy Association reported that in 2018, farmers and ranchers earned more than $280 million in lease payments from wind companies (American Wind Energy Association 2018). Potential social costs may include increased exposure to carcinogens, noise, and altered societal structures. Rural rangeland communities can become an industrial zone, including an influx of out-of-state workers and increase in crime that alters the quality of living in rangelands (CHPY and PSR 2016; Squillace 2016). Evaluating the societal values, costs, and benefits in the context of environmental effects before development can be used by state and regional planners to make effective decisions that allow a strategic approach to development and reduce the number and types of unwanted consequences.

During the energy development and construction phase

Opportunity—vegetation reclamation and restoration approaches

Measures can be taken to minimize damage to plant and soil systems (Baynard et al. 2017). Elimination of unwanted native or non-native weed species from a site before development can minimize the spread and dominance of such species in the disturbance area. Preliminary weed management of a site would benefit from including surrounding areas from which weeds can move into the disturbed site (Prach et al. 2015). If weeds do establish on an energy development site, they may stock the soil seed bank with weed seeds that will pose management challenges for years to come, so aggressive weed management is warranted up front.

Two approaches can be used to collect, preserve, and reduce the loss of a native plant community on an energy development site: salvage and stockpile topsoil and/or collect seeds from the plant community before disturbance or removal of that community. Seeds of local native plant ecotypes will be adapted to site conditions and represent an excellent, and perhaps superior, seed source for postdisturbance restoration. In addition to serving as a primary source of organic matter, nutrients, and soil biota, topsoil is a genetic repository of seeds from the indigenous plant community. These native soil seedbanks often represent the ideal seed mix for postdisturbance revegetation. Best management practices for storing and handling stockpiled topsoil have been developed in the coal mining industry and are summarized by Ferris et al. 2006. These practices include minimizing storage time, minimizing stockpile depths, and aggressively managing unwanted weedy species on the stockpile. However, long-term stock-piling ($>$ 2–4 yr) of soil may lead to permanent loss of native soil biota and seed banks. If multiple sites are planned to be disturbed within a short distance of one another over a decade, transfer of soil between sites may enable the native soil seed bank and potentially the native bud bank to be used rather than degrade if kept in a stockpile for multiple decades. Energy sites that will remain developed for multiple decades may never be able to be restored close to their former conditions. Mitigation might include directing funds to restore nearby habitats to improve overall regional environmental quality (Hull et al. 2016).

Restoration at coal mines has formed the historical basis of restoration practices in the energy sector. Coal mine reclamation was necessitated by an initial need to reduce erosion and sedimentation in surface waters in coal mining regions. As a result, there are numerous BMPs for erosion control available for the broader energy industry. Early revegetation practices in coal mine reclamation included the use of non-native plant species that could quickly provide high plant cover for minimizing erosion. In recent years, greater emphasis has been placed on the use of native plant species across all reclamation sectors creating new challenges since growing conditions for exotic cover crops are very different from the conditions needed to grow native plants. The challenges of restoring native plant communities on disturbed energy development sites has caused a shift in focus away from traditional approaches developed in coal mine reclamation toward more restoration-based approaches.

Restoration approaches differ from traditional reclamation in that there is greater emphasis on communities over species and on ecological processes over site physical conditions. This shift has led to wider recognition that increasing resource availability (fertilizer and water) is often counterproductive for establishing native vegetation, as these practices tend to favor undesirable plant species (Perry et al. 2010). In restoration, a greater emphasis is placed on understanding and manipulating mechanisms that cause shifts in plant communities during ecological succession (Call and Roundy 1991). This has led to the increased use of native early-successional species that grow well in postdisturbance environments (Herron et al. 2013; Uselman et al. 2015) and allow for the development of soil biological communities that are necessary for the establishment of resilient, native, late-successional plant communities (Busby et al. 2011).

Ecological restoration following energy development can be tailored to maximize native species diversity. Ecologists have long recognized that biodiversity imparts higher productivity and greater resilience to ecosystems (Schultz and Mooney 1993). For example, a recent analysis of 1126 grassland study plots across 5 continents revealed a strong and consistent link between productivity and species richness (Grace et al. 2016). Numerous studies have demonstrated that productivity of diverse grassland plant communities is more resistant and resilient to drought than species-poor communities (e.g., Tilman and Downing 1994; Wagg et al. 2017). Recovery of plant community productivity after extreme climate events is strongly dependent on initial diversity (Isbell et al. 2015). A recent study in eastern Colorado found that grassland restoration success was maximized when seed mixtures contained 35 native plant species (Barr et al. 2017). Added benefits of promoting native plant species diversity in restored energy development areas include value to wildlife, insect pollinators, and aesthetics.

Beyond using more diverse native seed mixtures for restoration, restorations can benefit from increased site heterogeneity. For example, many traditional reclamation approaches employ uniform topsoil depth, seed distribution, irrigation, and fertilization across a site resulting in uniform plant communities. Creating site heterogeneity by applying treatments in a nonuniform or haphazard fashion will result in increased biodiversity (Lundholm and Larson 2003). Varying surface topography across the restoration site may also result in greater plant diversity (Biederman and Whisenant 2011; Hough-Snee et al. 2011). Such practices are still uncommon as many regulations are based on specifications that do not embrace heterogeneity.

Looking forward—vegetation research needs

Despite advances in restoration methods for energy development in the Great Plains, many challenges remain. Although significant progress in chemical and biological controls for weeds in restoration settings has been made, managers are still faced with the challenges of establishing native plant communities once the weeds are gone. These two battles of weed management and native plant establishment are often fought by managers at the same time. Since most weedy species are broadleaved forbs, herbicides meant for weed control may also take native forbs out of the system, resulting in an overabundance of grasses in restored plant communities. Grass overabundance is further boosted by restoration seed mixes that tend to favor grasses over forbs and shrubs due to the high price of native forb and shrub seed. Low forb abundance is often accepted as grasslands are generally perceived as grass-dominated systems and grasses are desired for livestock production. However, recent evidence of global declines in grassland bird species (Stanton et al. 2018), pollinators (Ollerton 2017), and insect communities in general (Habel et al. 2016) has created a desire to increase forb diversity in grassland ecosystems. Determining how to increase forb diversity in grassland restorations is a current research challenge. A related challenge is developing commercial seed sources of forbs and shrubs for use in the Great Plains. Other regions have successfully formed regional seed cooperatives to support the use and production of native ecotype seed (Smith 2017).

Soil storage and vegetation restoration techniques can still be improved. Additional research could shed better understanding on the biological processes occurring in stockpiled and salvaged topsoil (e.g., microbial response) that would improve methods for storing and moving topsoil. New restoration techniques could be developed and used for linear developments (e.g., pipelines) as these linear projects will have short periods of disturbance enabling restoration to take place immediately following disturbance. The area disturbed by pipelines will far exceed the area disturbed by energy pad installation. For example, active wells in North Dakota occupy ~39 000 ha, whereas oil and gas pipelines occupy ~83 000 ha (assuming a 15-m wide linear disturbance; based on data from Pipeline Safety Trust and ND Oil and Gas Commission 2018). Current restoration methods for pipelines generally follow those for other energy disturbances within the impacted habitat.

During the energy production phase

Opportunity—wildlife considerations

Effects of extractive energy development on wildlife are largely unknown (Post van der Burg et al. (2017). Other reviews (e.g., Hebblewhite 2011) suggest that most studies are not designed to properly assess these effects. Infrastructure modifications can be made in ways to limit the effects of lighting, roads, industrial noise, and vegetation loss (Bayne et al. 2008; Kociolek et al. 2011; Gaston et al. 2012). Renewable and nonrenewable energy developers are examining new best management practices and technology for reducing noise, road traffic, fragmentation, vertical structure, displacement, and direct mortality. Timing restrictions can be put in place to minimize disturbance during key life history periods for key species (e.g., suspension of oil and gas development activities near leks in eastern Wyoming of the greater sage-grouse in the spring). Companies are investigating consolidation of technician visits to energy development sites in an effort to minimize traffic to and from the site. Renewable energy technologies continue to evolve as wind turbines increase in size, and solar energy facilities deploy a variety of panels and configurations (Zayas et al. 2015; NREL 2016).

Looking forward—wildlife studies

Ongoing research on species interactions with and behavior near energy facilities is providing new information that energy developers and resource managers can use when siting and permitting new energy projects. Operational management strategies designed and tested to reduce direct wildlife mortality while maintaining energy project profitability are providing developers more options to reduce wildlife effects. An increased focus on experimental design quality can accelerate development of effective minimization strategies. Effective wildlife mitigation can be most readily achieved using information that is species and site specific, accounts for differences in scale among species (e.g., butterflies travel 100−250 m, whereas mule deer travel several to > 100 km; Butler et al. 2018), includes trophic levels and community networks (e.g., how may the predator community affect its prey, which in turn will impact the insect community), and is based on long-term studies (e.g., changes in behavior may not be apparent from short-term studies).

The effects of wind energy on collisions with birds and bats in the Great Plains are relatively understudied compared with other regions of the United States (Erickson et al. 2014). Of the 53 facilities in the contiguous United States from which data were used by Loss et al. (2013) to analyze bird and bat collision mortality, only 10 facilities were located in 10 Great Plains states. While some of the first reports of collision mortality date back to 1976, mortality data availability, quality, and lack of standardization remain a limitation (Loss et al. 2013; Thompson Beston et al. 2017; Conkling et al. 2020). In addition, few studies have employed a rigorous statistical design, such as the “before and after control impact” (BACI) study design, which requires multiyear preconstruction and postconstruction surveys and the use of reference sites (Strickland et al. 2011). Using a BACI design, Shaffer and Buhl (2016) were able to detect immediate versus delayed displacement of nine breeding bird species, emphasizing the need and benefit of conducting more BACI-designed studies. With wind energy expected to continue to expand in the Great Plains because of the wind resource available (NREL 2016), competitive costs, and interest from landowners who can colocate wind facilities with cropland, pasture land, and even oil and gas wells (Davis et al. 2018), more rigorous research will be needed as these facilities evolve and become more numerous in the Great Plains.

Opportunities—monitoring resource use, emissions, and byproduct release

Emissions are produced while energy is being harvested, transported, or converted into more useable forms (e.g., power plants). The Great Plains are home to some of the largest shale plays in the United States, leading to increases in pollutant emissions. These have been offset, to some extent, by decreases in emissions from regional coal-fired power plants. Historically, legislation has been aimed at curbing emissions from coal-fired power plants, such as sulfur dioxide and nitrogen oxides. Regulations aimed at reducing emissions of these have been very successful (see Fig. 4). The net result of emission reductions from power plants has been a dramatic improvement in visibility (Hand et al. 2014), decreased occurrence of acidic precipitation (Lehmann and Gay 2011), and reductions in sulfate and nitrate deposition (NADP; http://nadp.slh.wisc.edu/data/) across the country.

Air quality can be monitored in the Great Plains. Critical loads are a useful tool for assessing the effect of nitrogen deposition on the condition of resources on federal lands (Pardo et al. 2015), and tools are available to support land managers in understanding whether their region is at risk (e.g., https://clmapper.epa.gov/). For ozone damage, certain species of plants (e.g., milkweed), called bioindicators, have distinct foliar injury symptoms and can be used to monitor ozone stress to the ecosystem as demonstrated by the ozone biomonitoring program in US forests (https://www.nrs.fs.fed.us/fia/topics/ozone/ ; Smith et al. 2008; Smith et al. 2012). Throughout the Great Plains, ecosystems are sensitive to air pollutant effects, and these effects must be taken into account when monitoring the state of local resources or when planning restoration activities. Effective monitoring will enable more informed mitigation measures.

Looking forward—atmospheric research

Although energy development occurs throughout the Great Plains, little research on air quality effects and their ecological implications have been conducted. Fundamental studies characterizing critical loads of key pollutants and ozone sensitivity of native species need to continue in the Great Plains. Additionally, comprehensive studies following the life cycle of air pollutants from energy-related emissions to measurable air quality impacts to quantitative ecological effects are needed to focus mitigation efforts. Studies that account for other regional disturbances can assist with untangling the effects of energy development from other non−energy-related disturbances (Brook et al. 2019).

Conclusions

Energy development can offer great economic opportunities in rural communities and provides a valuable commodity for society. However, energy development can stress grassland ecosystem services by affecting vegetation, wildlife, and human well-being. All large-scale renewable and nonrenewable energy types disturb or fragment wildlife habitat and introduce infrastructure on the landscape but differ in their land use efficiency. Infrastructure associated with energy extraction and transport introduces soil disturbance that can disrupt plant communities and increase soil erosion. Water resources and atmospheric conditions can deteriorate due to chemical discharges or emissions at the site of energy harvest.

Grassland managers, community planners, and local, state, and federal governments have and will continue to apply options to avoid, reduce, and mitigate effects of energy development. Energy development effects can be mitigated during the planning phase by considering energy development alternatives and effects on the environment, as well as societal values. Vegetation reclamation efforts can reduce soil erosion and help reclaim disturbed land during and following energy development. Monitoring of water and atmospheric quality can keep managers aware of potential changes occurring within grassland systems. Future research addressing the effects of cumulative energy development in a region, developing techniques and seed supplies for native plant establishment following ground disturbance, producing before-after-control-impact studies for species and site-specific wildlife concerns, and identifying critical loads of key pollutants will enable managers to better respond to energy development concerns. As managers find themselves at different points in the energy development cycle or as regional planners consider broad-scale energy development in the Great Plains, this review can serve as a starting point to identify potential environmental concerns and mitigation options available to them at each point in the energy development cycle. Energy development and production will continue throughout the Great Plains. The diverse group of stakeholders involved in energy development will need to continue to define priorities, incorporate research findings, and find ways to work together to address energy development's effects in a way that enables energy to be produced while conserving the integrity of the grassland ecosystem.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Allred, B.W., Smith, W.K., Twidwell, D., Haggerty, J.H., Running, S.W., Naugle, D.E., Fuhlendorf, S.D., 2015. Ecosystem services lost to oil and gas in North America. Science 348, 401–402.

Ahmadi, M., John, K., 2015. Statistical evaluation of the impact of shale gas activities on ozone pollution in North Texas. Science of the Total Environment 536, 457–467.

Ainsworth, E.A., Yendrek, C.R., Sitch, S., Collins, W.J., Emberson, L.D., 2012. The effects of tropospheric ozone on net primary productivity and implications for climate change. *In*: Merchant, S. S. [ed.]. Annual review of plant biology 63, 637–661.

Allen, D.T., 2016. Emissions from oil and gas operations in the United States and their air quality implications. Journal of the Air & Waste Management Association 66, 549–575.

Allen, D.T., Torres, V.M., Thomas, J., Sullivan, D.W., Harrison, M., Hendler, A., Herndon, S.C., Kolb, C.E., Fraser, M.P., Hill, A.D., Lamb, B.K., Miskimins, J., Sawyer, R.F., Seinfeld, J.H., 2013. Measurements of methane emissions at natural gas production sites in the United States. Proceedings of the National Academy of Sciences of the United States of America 110, 17768–17773.

American Wind Energy Association. 2018. US. Wind Industry Annual Market Report, Year Ending 2018. Available at: https://www.awea.org. Accessed June 16. 2020.

American Wind Energy Association, US Wind Industry Second Quarter 2019 Market Report. Available at: https://www.awea.org/2019marketreports. Accessed on October 8, 2019.

Arnett, E.B., Brown, W.K., Erickson, W.P., Fiedler, J.K., Hamilton, B.L., Henry, T.H., Jain, A., Johnson, G.D., Kerns, J., Koford, R.R., Nicholson, C.P., O'Connell, T.J., Piorkowski, M.D., Tankersley, R.D., 2008. Patterns of bat fatalities at wind energy facilities in North America. Journal of Wildlife Management 72, 61–78.

Arnett, E.B., Inkley, D.B., Johnson, D.H., Larkin, R.P., Manes, S., Manville, A.M., Mason, J.R., Morrison, M.L., Strickland, M.D., Thresher, R., 2007. Impacts of wind energy facilities on wildlife and wildlife habitat—Wildlife Society technical review 07-2. The Wildlife Society, Bethesda, MD, USA.

Auers, J.R., Coutre, R.M., Sutton, D.L., 2014. The North Dakota Petroleum Council Study on Bakken Crude Properties. North Dakota Petroleum Council 78.

Bader, W., Bovy, B., Conway, S., Strong, K., Smale, D., Turner, A.J., Blumenstock, T., Boone, C., Coen, M.C., Coulon, A., Garcia, O., Griffith, D.T., Hase, F., Hausmann, P., Jones, N., Krummel, P., Murata, I., Morino, I., Nakajima, H., O'Doherty, S., Paton-Walsh, C., Robinson, J., Sandrin, R., Schneider, M., Servais, C., Sussmann, R., Mahieu, E., 2017. The recent increase of atmospheric methane from 10 years of ground-based NDACC FTIR observations since 2005. Atmospheric Chemistry and Physics 17, 2255–2277.

Baer, S.G., Kitchen, D.J., Blair, J.M., Rice, C.W., 2002. Changes in ecosystem structure and function along a chronosequence of restored grasslands. Ecological Applications 12, 1688–1701.

Bar-Ilan, A., Grant, J., Parikh, R., and Morris, R. 2011. Oil and gas mobile sources pilot study: final report. Novato, California, USA. U.S. Environmental Protection Agency Work Assignment 4-08. p. 41.

Barr, S., Jonas, J.L., Paschke, M.W., 2017. Optimizing seed mixture diversity and seeding rates for grassland restoration. Restoration Ecology 25, 396–404.

Bassin, S., Volk, M., Fuhrer, J., 2007. Factors affecting the ozone sensitivity of temperate European grasslands: an overview. Environmental Pollution 146, 678–691.

Baynard, C.W., Mjachina, K., Richardson, R.D., Schupp, R.W., Lambert, J.D., Chibilyev, A.A., 2017. Energy development in Colorado's Pawnee national grasslands: mapping and measuring the disturbance footprint of renewables and non-renewables. Environmental Management 59, 995–1016.

Bayne, E.M., Dale, B.C., 2011. Effects of energy development on songbirds. In: Naugle, D.E (Ed.), Energy development and wildlife conservation in western North America. Island Press, Washington, D.C., USA, pp. 95–114.

Bayne, E.M., Dale, B.C., Naugle, D.E., 2011. Effects of energy development on songbirds p. 95-114. In: Naugle, D.E. (Ed.), Energy Development and Wildlife Conservation in Western North America. Island Press, Washington, D.C, USA, p. 230.

Bayne, E.M., Habib, L., Boutin, S., 2008. Impacts of chronic anthropogenic noise from energy-sector activity on abundance of songbirds in the boreal forest. Conservation Biology 22, 1186–1193.

Bee, M.A., Swanson, E.M., 2007. Auditory masking of anuran advertisement calls by road traffic noise. Animal Behaviour 74, 1765–1776. Available at: https://doi.org/10.1016/j.anbehav.2007.03.019.

Benítez-López, A., Alkemade, R., Verweij, P.A., 2010. The impacts of roads and other infrastructure on mammal and bird populations—a meta-analysis. Biological Conservation 143, 1307–1316. Available at: https://doi.org/10.1016/j.biocon.2010.02.009.

Biederman, L.A., Whisenant, S.G., 2011. Using mounds to create microtopography alters plant community development early in restoration. Restoration Ecology 19, 53–61.

Blickley, J.L., Blackwood, D., Paticelli, G.L., 2012. Experimental evidence for the effects of chronic anthropogenic noise on abundance of greater sage-grouse at leks. Conservation Biology 26, 461–471.

Boehm, P.D., Gunlach, E.R., Page, D.S., 2013. The phases of an oil spill and scientific studies of spill effects. In: Wiens (Ed.), Oil in the Environment: Legacies and Lessons of the Exxon Valdez Oil Spill. Cambridge University Press, New York, NY, USA, pp. 37–56.

Brandt, A.R., Heath, G.A., Kort, E.A., O'Sullivan, F., Petron, G., Jordaan, S.M., Tans, P., Wilcox, J., Gopstein, A.M., Arent, D., Wofsy, S., Brown, N.J., Bradley, R., Stucky, G.S., Eardley, D., Harriss, R., 2014. Methane leaks from North American natural gas systems. Science 343, 733–735.

Brittingham, M.C., Maloney, K.O., Farag, A.M., Harper, D.D., Bowen, Z.H., 2014. Ecological risks of shale oil and gas development to wildlife, aquatic resources and their habitats. Environmental Science & Technology 48, 11034–11047. Available at: https://doi.org/10.1021/es5020482.

Brook, J. R., Cober, S. G., Freemark, M., Harner, T., Li, S. M., Liggio, J., Makar, P., and Pauli, B. 2019. Advances in science and applications of air pollution monitoring: a case study on oil sands monitoring targeting ecosystem protection. Journal of the Air & Waste Management Association 69, 661–709. Available at https://doi.org/10.1080/10962247.2019.1607689.

Bunkley, J.P., McClure, C.J.W., Kawahara, A.Y., Francis, C.D., Barber, J.R., 2017. Anthropogenic noise changes arthropod abundances. Ecology and Evolution 7, 2977–2985.

Burr, P.C., Robinson, A.C., Larsen, R.T., Newman, R.A., Ellis-Felege, S.N., 2017. Sharp-tailed grouse nest survival and nest predator habitat use in North Dakota's Bakken oil field. PLoS ONE 12 (1), e0170177. Available at: https://doi.org/10.1371/journal.pone.0170177.

Busby, R.R., Gebhart, D.L., Stromberger, M.E., Meiman, P.J., Paschke, M.W., 2011. Early seral plant species' interactions with an arbuscular mycorrhizal fungi community are highly variable. Applied Soil Ecology 48, 257–262.

Butler, J.L., Ott, J.P., Hartway, C.R., Dickerson, B.E., 2018. Biological assessment of oil and gas development on the Little Missouri National Grassland. In: Gen. Tech. Rep. RMRS-GTR-384. Fort Collins, CO, USA: US Department of Agriculture, Forest Service. Rocky Mountain Research Station, p. 67.

Call, C.A., Roundy, B.A., 1991. Perspectives and processes in revegetation of arid and semiarid rangelands. Journal of Range Management 44, 543–549.

Carpenter, J., Aldridge, C., Boyce, M.S., 2010. Sage-grouse habitat selection during winter in Alberta. Journal of Wildlife Management 74, 1806–1814.

Carr, L.W., Fahrig, L., 2001. Effect of road traffic on two amphibian species of differing vagility. Conservation Biology 15, 1071–1078.

CHPY and PSR [Concerned Health Professionals of New York and Physicians for Social Responsibility]. 2016. Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking. Available at: http://concernedhealthny.org/compendium/. Accessed April 10, 2018.

Clark, C.M., 2011. Assessment of nitrogen deposition effects and empirical critical loads of nitrogen for ecoregions of the United States. USDA, US Forest Service, Northern Research Station, Newtown Square, PA, USA, pp. 117–132.

Conkling, T.J., Loss, S.R., Diffendorfer, J.E., Duerr, A., Katzner, T.E., 2020. Limitations, lack of standardization, and recommended best practices in studies of renewable energy effects on birds and bats. Conservation Biology. Available at: https://doi.org/10.1111/cobi.13457.

Cosentino, B.J., Marsh, D.M., Jones, K.S., Apodaca, J.J., Bates, C., Beach, J., Beard, K.H., Becklin, K., Bell, J.M., Crockett, C., Fawson, G., Fjelsted, J., Forys, E.A., Genet, K.S., Grover, M., Holmes, J., Indeck, K., Karraker, N.E., Kilpatrick, E.S., Langen, T.A., Mugel, S.G., Molina, A., Vonesh, J.R., Weaver, R.J., Willey, A., 2014. Citizen science reveals widespread negative effects of roads on amphibian distributions. Biological Conservation 180, 31–38. Available at: https://doi.org/10.1016/j.biocon.2014.09.027.

Cozzarelli, I.M., Skalak, K.J., Kent, D.B., Engle, M.A., Benthem, A., Mumford, A.C., Haase, K., 2017. Environmental signatures and effects of an oil and gas wastewater spill in the Williston Basin, North Dakota. Science of The Total Environment 579, 1781–1793. https://doi.org/10.1016/j.scitotenv.2016.11.157.

Craig, E.H., Fuller, M.R., Craig, T.H., Huettmann, F., 2018. Assessment of potential risks from renewable energy development and other anthropogenic factors to wintering golden eagles in the western United States. In: Humphries, G., Magness, D., Huettmann, F. (Eds.), Machine learning for ecology and sustainable natural resource management. Springer, Cham, Switzerland. Available at: https://doi.org/10.1007/978-3-319-96978-7_19.

D'Amico, M., Périquet, S., Román, J., Revilla, E., 2016. Road avoidance responses determine the impact of heterogeneous road networks at a regional scale. Journal of Applied Ecology 53, 181–190.

Davidsson, S., Höök, M., Wall, G., 2012. A review of life cycle assessments on wind energy systems. The International Journal of Life Cycle Assessment 17, 729–742.

Davis, K.M., Nguyen, M.N., McClung, M.R., Moran, M.D., 2018. A comparison of the impacts of wind energy and unconventional gas development on land-use and ecosystem services: an example from the Anadarko Basin of Oklahoma, USA. Environmental Management 61, 796–804.

De Molenaar, J.G., Sanders, M.E., Jonkers, D.A., Rich, C., Longcore, T., 2006. Roadway lighting and grassland birds—local influence of road lighting on a black--tailed godwit population. In: Rich, C., Longcore, T. (Eds.), Ecological consequences of artificial night lighting. Island Press, Washington, D.C., USA, pp. 114–136.

Diffendorfer, J.E., Dorning, M.A., Keen, J.R., Kramer, L.A., Taylor, R.V., 2019. Geographic context affects the landscape change and fragmentation caused by wind energy facilities. PeerJ 7, e7129. Available at: http://doi.org/10.7717/peerj.7129.

Dorning, M.A., Garman, S.L., Diffendorfer, J.E., Semmens, D.J., Hawbaker, T.J., Bagstad, K.J., 2017. Oil and gas development influences big-game hunting in Wyoming. Journal of Wildlife Management 81, 3–379.

Duerr, A.E., Miller, T.A., Dunn, L., Bell, D.A., Bloom, P.H., Fisher, R.N., Tracey, J.A., Katzner, T.E., 2019. Topographic drivers of flight altitude over large spatial and temporal scales. The Auk 136:ukz002. Available at: https://doi.org/10.1093/auk/ukz002.

Dzialak, M.R., Harju, S.M., Osborn, R.G., Wondzell, J.J., Hayden-Wing, L.D., Winstead, J.B., Webb, S.L., 2011. Prioritizing conservation of ungulate calving resources in multiple-use landscapes. PLoS One 6. Available at: https://doi.org/10.1371/journal.pone.0014597.

Eagles-Smith, C. A., Willacker, J. J., and Flanagan Pritz, C. M. 2014. Mercury in fishes from 21 national parks in the Western United States—Inter and intra-park variation in concentrations and ecological risk. *U.S. Geological Survey Open-File Report* 2014-1051. p. 54.

Energy Information Administration (EIA). 2018. Annual energy outlook 2018 with projections to 2050. Washington, DC, USA: EIA. Available at: www.eia.gov/aeo. Accessed April 10, 2018.

Energy Information Administration (EIA), 2019. US Annual Coal Report. EIA, Washington, DC, USA. Available at: www.eia.gov/coal/annual/pdf/table1.pdf.

Energy of North Dakota (END). 2020. How oil is produced: drilling and production. Bismarck, ND, USA. Available at: https://energyofnorthdakota.com/home-menu/how-oil-is-produced/drilling-production/. Accessed January 2, 2020.

Entrekin, S.A., Maloney, K.O., Kapo, K.E., Walters, A.W., Evans-White, M.A., Klemow, K.M., 2015. Stream vulnerability to widespread and emergent stressors: a focus on unconventional oil and gas. PloS One. Available at: https://doi.org/10.1371/journal.pone.0137416.

Environmental Protection Agency (EPA). 2011. National listing fish advisories. Available at: https://www.epa.gov/fish-tech/national-listing-fish-advisories-2011-data. Accessed April 10, 2018.

Epstein, P.R., Buonocore, J.J., Eckerle, K., Hendryx, M., Stout Iii, B.M., Heinberg, R., Clapp, R.W., May, B., Reinhart, N.L., Ahern, M.M., Doshi, S.K., Glustrom, L., 2011. Full cost accounting for the life cycle of coal. Annals of the New York Academy of Sciences 1219, 73–98.

Erickson, W.P., Johnson, G.D., Young, D.P., Ralph, C.J., Rich, T.D., 2005. A summary and comparison of bird mortality from anthropogenic causes with an emphasis on collisions. US Forest Service, Albany, CA, USA, p. 1042 p. 1029 & #8722.

Erickson, W.P., Wolfe, M.M., Bay, K.J., Johnson, D.H., Gehring, J.L., 2014. A comprehensive analysis of small-passerine fatalities from collision with turbines at wind energy facilities. PLoS One 9, e107491. Available at: https://doi.org/10.1371/journal.pone.0107491.

Evangelista, P.H., Crall, A.W., Bergquist, E., Naugle, D.E., 2011. Invasive plants and their response to energy development. In: Naugle, D.E. (Ed.), Energy development and wildlife conservation in western North America. Island Press, New York, NY, USA, p. 129 p. 115–129.

Evanoski-Cole, A.R., Gebhart, K.A., Sive, B.C., Zhou, Y., Capps, S.L., Day, D.E., Prenni, A.J., Schurman, M.I., Sullivan, A.P., Li, Y., Hand, J.L., Schichtel, B.A., Collett, J.L., 2017. Composition and sources of winter haze in the Bakken oil and gas extraction region. Atmospheric Environment 156, 77–87.

Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L.C., Biak, D.R.A., Madaeni, S.S., Abidin, Z.Z., 2009. Review of technologies for oil and gas produced water treatment. Journal of Hazardous Materials 170, 2–3. Available at: https://doi.org/10.1016/j.jhazmat.2009.05.044.

Fargione, J., Kiesecker, J., Slaats, M.J., Olimb, S., 2012. Wind and wildlife in the Northern Great Plains: identifying low-impact areas for wind development. PLos One 7, e41468. doi:10.1371/journal.pone.0041468.

Fenn, M.E., Baron, J.S., Allen, E.B., Rueth, H.M., Nydick, K.R., Geiser, L., Bowman, W.D., Sickman, J.O, Meixner, T., Johnson, D.W., Neitlich, P., 2003. Ecological effects of nitrogen deposition in the western United States. Bioscience 53, 404–420.

Ferris, F.K., Kleinman, L.H., Postovit, B.C., Steward, D.G., Stowe, R.L., Vicklund, L.E., 2006. Handbook of western reclamation techniques, 2nd ed.. US Office of Surface Mining Reclamation and Enforcement, Denver, CO, USA, p. 504.

Field, R.A., Soltis, J., Murphy, S., 2014. Air quality concerns of unconventional oil and natural gas production. Environmental Science-Processes & Impacts 16, 954–969.

Forman, R.T.T., Reineking, B., Hersperger, A.M., 2002. Road traffic and nearby grassland bird patterns in a sub-urbanizing landscape. Environmental Management 29, 782–800.

Francis, C.D., Kleist, N.J., Ortega, C.P., Cruz, A., 2012. Noise pollution alters ecological services: enhanced pollination and disrupted seed dispersal. Proceedings of the Royal Society B 279, 2727–2735.

Francis, C.D., Barber, J.R., 2013. A framework for understanding noise impacts on wildlife—an urgent conservation priority. Frontiers in Ecology and the Environment 11, 305–313. Available at: https://doi.org/10.1890/120183.

Gaff, B.J., Jenks, J.A., Stafford, J.D., Jensen, K.C., Grovenburg, T.W., 2016. Assessing spring direct mortality to avifauna from wind energy facilities in the Dakotas. Journal of Wildlife Management 80, 736–745. Available at: http://dx.doi.org/10.1002/jwmg.1051.

Garrah, E., Danby, R.K., Eberhardt, E., Cunnington, G.M., Mitchell, S., 2015. Hot spots and hot times—wildlife road mortality in a regional conservation corridor. Environmental Management 56, 874–889.

Gaston, K.J., Davies, T.W., Bennie, J., Hopkins, J., 2012. Reducing the ecological consequences of night-time light pollution—options and developments. Journal of Applied Ecology 49, 1256–1266.

Gaston, K.J., Duffy, J.P., Gaston, S., Bennie, J., Davies, T.W., 2014. Human alteration of natural light cycles–Causes and ecological consequences. Oecologia 176, 917–931.

Gauthreaux, S.A., Belser, C.G., 2006. Effects of artificial night lighting on migrating birds. Island Press, Washington, DC, USA, pp. 67–93.

Gilbert, M.M., Chalfoun, A.D., 2011. Energy development affects populations of sagebrush songbirds in Wyoming. Journal of Wildlife Management 75, 816–824. Available at: https://doi.org/10.1002/jwmg.123.

Gleason, R.A., Tangen, B.A., 2014. Brine contamination to aquatic resources from oil and gas development in the Williston Basin. United States: US Geological Survey Scientific Investigations Report 2014. 127−127Available at: https://doi.org/10.3133/sir20145017.

Goodwin, M.J., Musa, O.M., Steed, J.W., 2015. Problems associated with sour gas in the oilfield industry and their solutions. Energy & Fuels 29, 4667–4682.

Gordalla, B.C., Ewers, U., Frimmel, F.H., 2013. Hydraulic fracturing: a toxicological threat for groundwater and drinking-water. Environmental Earth Sciences 70, 3875–3893. Available at: https://doi.org/10.1007/s12665-013-2672-9.

Grace, J.B., Anderson, T.M., Seabloom, E.W., Borer, E.T., Adler, P.B., Harpole, W.S., Hautier, Y., Hillebrand, H., Lind, E.M., Pärtel, M., Bakker, J.D., Buckley, Y.M., Crawley, M.J., Damschen, E.I., Davies, K.F., Fay, P.A., Firn, J., Gruner, D.S., Hector, A., Knops, J.M., MacDougall, A.S., Melbourne, B.A., Morgan, J.W., Orrock, J.L., Prober, S.M., Smith, M.D., 2016. Nature 529, 390–393.

Habel, J.C., Segerer, A., Ulrich, W., Torchyk, O., Weisser, W.W., Schmitt, T., 2016. Butterfly community shifts over two centuries. Conservation Biology 30, 754–762.

Habib, L., Bayne, E.M., Boutin, S., 2007. Chronic industrial noise affects pairing success and age structure of ovenbirds *Seiurus aurocapilla*. Journal of Applied Ecology 44, 176–184.

Halliday, H.S., Thompson, A.M., Wisthaler, A., Blake, D.R., Hornbrook, R.S., Mikoviny, T., Muller, M., Eichler, P., Apel, E.C., Hills, A.J., 2016. Atmospheric benzene observations from oil and gas production in the Denver-Julesburg Basin in July and August 2014. Journal of Geophysical Research-Atmospheres 121, 11055–11074.

Hamilton, L.E., Dale, B.C., Paszkowski, C.A., 2011. Effects of disturbance associated with natural gas extraction on the occurrence of three grassland songbirds. Avian Conservation and Ecology 6.

Hand, J.L., Gebhart, K.A., Schichtel, B.A., Malm, W.C., 2012. Increasing trends in wintertime particulate sulfate and nitrate ion concentrations in the Great Plains of the United States (2000-2010). Atmospheric Environment 55, 107–110.

Hand, J.L., Schichtel, B.A., Malm, W.C., Copeland, S., Molenar, J.V., Frank, N., Pitchford, M., 2014. Widespread reductions in haze across the United States from the early 1990s through 2011. Atmospheric Environment 94, 671–679.

Harrison, J.O., Brown, M.B., Powell, L.A., Schacht, W.H., Smith, J.A., 2017. Nest site selection and nest survival of Greater Prairie-Chickens near a wind energy facility. The Condor 119, 659–672. Available at: http://americanornithologypubs.org/doi/pdf/10.1650/CONDOR-17-51.1.

Hebblewhite, M., Naugle, D.E., 2011. Effects of energy development on ungulates. Island Press, Washington, DC, USA, pp. 71–94.

Hels, T., Buchwald, E., 2001. The effects of road kills on amphibian populations. Biological Conservation 99, 331–340.

Herron, C.M., Jonas, J.L., Meiman, P.J., Paschke, M.W., 2013. Using native annual plants to restore post-fire habitats in western North America. International Journal of Wildland Fire 22, 815–821.

Hethcoat, M.G., Chalfoun, A.D., 2015. Energy development and avian nest survival in Wyoming, USA—a test of a common disturbance index. Biological Conservation 184, 327–334. Available at: https://doi.org/10.1016/j.biocon.2015.02.009.

Hill, J., Polasky, S., Nelson, E., Tilman, D., Huo, H., Ludwig, L., Neumann, J., Zheng, H., Bonta, D., 2009. Climate change and health costs of air emissions from biofuels and gasoline. Proceedings of the National Academy of Sciences 106, 2077.

Hoen, B. D., Diffendorfer, J. E., Rand, J. T., Kramer, L. A., Garrity, C. P., and Hunt, H. E. 2018. United States Wind Turbine Database. US Geological Survey, American Wind Energy Association, and Lawrence Berkeley National Laboratory data release: USWTDB V1.3 (January 7, 2019). Available at: https://eerscmap.usgs.gov/uswtdb. Accessed April 9, 2019.

Hough-Snee, N., Long, A.L., Jeroue, L., Ewing, K., 2011. Mounding alters environmental filters that drive plant community development in a novel grassland. Ecological Engineering 37, 1932–1936.

Howarth, R.W., Santoro, R., Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change 106, 679–690.

Hull, R.N., Luoma, S.N., Bayne, B.A., Iliff, J., Larkin, D.J., Paschke, M.W., Victor, S.L., Ward, S.E., 2016. Opportunities and challenges of integrating ecological restoration into assessment and management of contaminated ecosystems. Integrated Environmental Assessment and Management 12, 296–305.

Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmidt, B., Beierkuhnlein, C., Bezemer, T.M., Bonin, C., Bruelheide, H., de Luca, E., Ebeling, A., Griffin, J.N., Guo, Q., Hautier, Y., Hector, A., Jentsch, A., Kreyling, J., Lanta, V., Manning, P., Meyer, S.T., Mori, A.S., Naeem, S., Niklaus, P.A., Polley, H.W., Reich, P.B., Roscher, C., Seabloom, E.W., Smith, M.D., Thakur, M.P., Tilman, D., Tracey, B.F., van der Putten, W.H., van Ruijven, J., Weigelt, A., Weisser, W.W., Wilsey, B., Eisenhauer, N.F., 2015. Biodiversity increases the resistance of ecosystem productivity to climate extremes. Nature 526, 574–577.

Jackson, R.B., Vengosh, A., Carey, J.W., Davies, R.J., Darrah, T.H., O'Sullivan, F., Petron, G., 2014. The environmental costs and benefits of fracking. Annual Review of Environmental Resources 39, 327–362.

Jones, D.L., 2010. Potential air emission impacts of cellulosic ethanol production at seven demonstration refineries in the United States. Journal of the Air & Waste Management Association 60, 1118–1143.

Jorgensen, E.E., Holub, S.M., Mayer, P.M., Gonsoulin, M.E., Silva, R.G., West, A.E., Tunnell, S.J., Clark, J.E., Parsons, J.L., Engle, D.M., Hellgren, E.C., Spears, J.D.H., Butler, C.E., Leslie, D.M.J., 2005. Ecosystem stress from chronic exposure to low levels of nitrate. EPA/600/R-05/087. Environmental Protection Agency, National Risk Management Research Laboratory, Washington, DC, USA, p. 35.

Katzner, T., Brandes, D., Miller, T., Lanzone, M., Maisonneuve, C., Tremblay, Mulvihill, R., Merovich, G., 2012. Topography drives migratory flight altitude of Golden Eagles: implications for on-shore wind energy development. Journal of Applied Ecology 49, 1178–1186.

Khalil, M. [ed.]. 2018. US Geological survey energy and wildlife research annual report for 2018 (ver. 1.1, October 2018): US Geological Survey Circular. 1447:102. Available at: https://doi.org/10.3133/cir1447.

Kharaka, Y.K., Otton, J.K., 2003. Environmental impacts of petroleum production: initial results from the Osage-Skiatook petroleum environmental research sites, Osage County. US Geological Survey Water-Resources Investigations Report 3 155−155.

Kociolek, A.V., Clevenger, A.P., St. Clair, C.C., Proppe, D.S., 2011. Effects of road networks on bird populations. Conservation Biology 25, 241–249.

Kohut, R., 2007. Assessing the risk of foliar injury from ozone on vegetation in parks in the US National Park Service's vital signs network. Environmental Pollution 149, 348–357.

Kolar, J.L., Millspaugh, J.J., Stillings, B.A., Hansen, C.P., Chitwood, C., Rota, C.T., Skelly, B.P., 2017. Potential effects of oil and gas energy development on mule deer in western North Dakota. Final report. North Dakota Game and Fish Department, Dickinson, ND, USA.

Kolowski, J., Alonso, A., 2010. Density and activity patterns of ocelots *(Leopardus pardalis)* in northern Peru and the impact of oil exploration activities. Biological Conservation 143, 917–925. Available at: https://doi.org/10.1016/j.biocon.2009.12.039.

Kort, E.A., Smith, M.L., Murray, L.T., Gvakharia, A., Brandt, A.R., Peischl, J., Ryerson, T.B., Sweeney, C., Travis, K., 2016. Fugitive emissions from the Bakken shale illustrate role of shale production in global ethane shift. Geophysical Research Letters 43, 4617–4623.

Koss, A., Yuan, B., Warneke, C., Gilman, J.B., Lerner, B.M., Veres, P.R., Peischl, J., Eilerman, S., Wild, R., Brown, S.S., Thompson, C.R., Ryerson, T., Hanisco, T., Wolfe, G.M., Clair, J.M.S., Thayer, M., Keutsch, F.N., Murphy, S., De Gouw, J., 2017. Observations of VOC emissions and photochemical products over US oil- and gas-producing regions using high-resolution H3O+ CIMS (PTR-ToF-MS). Atmospheric Measurement Techniques 10, 2941–2968.

Kroepsch, A.C., 2018. Horizontal drilling, changing patterns of extraction, and piecemeal participation: urban hydrocarbon governance in Colorado. Energy Policy 120, 469–480.

Kurth, L., Kolker, A., Engle, M., Geboy, N., Hendryx, M., Orem, W., McCawley, M., Crosby, L., Tatu, C., Varonka, M., DeVera, C., 2015. Atmospheric particulate matter in proximity to mountaintop coal mines: sources and potential environmental and human health impacts. Environmental Geochemistry and Health 37, 529–544.

Lago, C., Prades, A., Lechón, Y., Oltra, C., Pullen, A., and Auer, H. 2009. Wind energy—the facts: environmental issues. Available at: https://wind-energy-the-facts.org/images/chapter5.pdf. Accessed April 10, 2018.

Lapina, K., Henze, D.K., Milford, J.B., Huang, M., Lin, M.Y., Fiore, A.M., Carmichael, G., Pfister, G.G., Bowman, K., 2014. Assessment of source contributions to seasonal vegetative exposure to ozone in the US. Journal of Geophysical Research-Atmospheres 119, 324–340.

Lauenroth, W.K., Burke, I.C., Gutmann, M.P., 1999. The structure and function of ecosystems in the central North American grassland region. Great Plains Research 9, 223–259.

LeBeau, C., Beck, J.L., Johnson, G.D., Holloran, M.J., 2014. Short-term impacts of wind energy development on greater sage-grouse fitness. Journal of Wildlife Management 78, 522–530.

Leddy, K.L., Higgins, K.F., Naugle, D.E., 1999. Effects of wind turbines on upland nesting birds in Conservation Reserve Program grasslands. Wilson Bulletin 111, 100–104.

Lefohn, A.S., Jackson, W., Shadwick, D.S., Knudsen, H.P., 1997. Effect of surface ozone exposures on vegetation grown in the southern Appalachian mountains: identification of possible areas of concern. Atmospheric Environment 31, 1695–1708.

Lefohn, A.S., Laurence, J.A., Kohut, R.J., 1988. A comparison of indexes that describe the relationship between exposure to ozone and reduction in the yield of agricultural crops. Atmospheric Environment 22, 1229–1240.

Lehmann, C.M., Gay, D.A., 2011. Monitoring long-term trends of acidic wet deposition in US precipitation: results from the National Atmospheric Deposition Program. PowerPlant Chemistry 13, 378–385.

Loesch, C.R., Walker, J.A., Reynolds, R.E., Gleason, J.S., Niemuth, N.D., Stephens, S.E., Erickson, M.A., 2013. Effect of wind energy facilities on breeding duck densities in in the Prairie Pothole Region. Journal of Wildlife Management 77, 587–598.

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

Ludlow, S.M., Brigham, R.M., Davis, S.K., 2015. Oil and natural gas development has mixed effects on the density and reproductive success of grassland songbirds. Condor Ornithology Applications 117, 64–75.

Lundholm, J.T., Larson, D.W., 2003. Relationships between spatial environmental heterogeneity and plant species diversity on a limestone pavement. Ecography 26, 715–722.

Lyon, D.R., Alvarez, R.A., Zavala-Araiza, D., Brandt, A.R., Jackson, R.B., Hamburg, S.P., 2016. Aerial surveys of elevated hydrocarbon emissions from oil and gas production sites. Environmental Science & Technology 50, 4877–4886.

Maupin, M. A., Kenny, J. F., Hutson, S. S., Lovelace, J. K., Barber, N. L., and Linsey, K. S. 2014. Estimated use of water in the United States in 2010: US Geological Survey Circular. 1405:56. Available at: http://dx.doi.org/10.3133/cir1405.

McBroom, M., Thomas, T., Zhang, Y., 2012. Soil erosion and surface water quality impacts of natural gas development in east Texas. Water 4, 944–958. Available at: https://doi.org/10.3390/w4040944.

McClung, M.R., Taylor, N.T., Samzow, B.K., Taylor Stone, E., Abad, H., Moran, M.D., 2019. The threat of energy diversification to a bioregion: a landscape-level analysis of current and future impacts on the US Chihuahuan Desert. Regional Environmental Change 19, 1949–1962.

McLinden, C.A., Fioletov, V., Krotkov, N.A., Li, C., Boersma, K.F., Adams, C., 2016. A decade of change in NO_2 and SO_2 over the Canadian oil sands as seen from space. Environmental Science & Technology 50, 331–337.

McNew, L.B., Hunt, L.M., Gregory, A.J., Wisely, S.M., Sandercock, B.K., 2014. Effects of wind energy development on nesting ecology of greater prairie-chickens in fragmented grasslands. Conservation Biology 28, 1089–1099.

Millstein, D., Wiser, R., Bolinger, M., Barbose, G., 2017. The climate and air-quality benefits of wind and solar power in the United States. Nature Energy 2, 17134, Available at: https://doi.org/10.1038/nenergy.2017.134.

Miller, T.A., Brooks, R.P., Lanzone, M., Brandes, D., Cooper, J., O'Malley, K., Maisonneuve, C., Tremblay, J., Duerr, A., Katzner, T., 2014. Assessing risk to birds from industrial wind energy development via paired resource selection models. Conservation Biology 28, 745–755.

Moran, M.D., Cox, A.B., Wells, R.L., Benichou, C.C., McClung, M.R., 2015. Habitat loss and modification due to gas development in the Fayetteville Shale. Environmental Management 55, 1276–1284.

Morefield, P.E., LeDuc, S.D., Clark, C.M., Iovanna, R., 2016. Grasslands, wetlands, and agriculture: the fate of land expiring from the Conservation Reserve Program in the Midwestern United States. Environmental Research Letters 11, 094005.

Moseley, K.R., Ford, W.M., Edwards, J.W., 2009. Local and landscape scale factors influencing edge effects on woodland salamanders. Environmental Monitoring and Assessment 151, 425–435.

Mushet, D.M., 2010. From Earth observing space satellites to nuclear microsatellites: amphibian conservation in the northern Great Plains [dissertation]. North Dakota State University, Fargo, ND, USA, p. 134.

Nasen, L.C., Noble, B.F., Johnstone, J.F., 2011. Environmental effects of oil and gas lease sites in a grassland ecosystem. Journal of Environmental Management 92, 195–204.

National Renewable Energy Laboratory (NREL). 2016. Renewable Energy Data Book. Available at: https://www.nrel.gov/docs/fy18osti/70231.pdf. Accessed March 20, 2019.

ND Oil and Gas Commission. 2018. Available at: https://www.dmr.nd.gov/oilgas/stats/historicaloilprodstats.pdf. Accessed March 28, 2019.

New, L., Bjerre, E., Millsap, B., Otto, M.C., Runge, M.C., 2015. A collision risk model to predict avian fatalities at wind facilities: an example using Golden Eagles. Aquila chrysaetos. PLoS ONE 10 (7), e0130978. Available at: https://doi.org/10.1371/journal.pone.0130978.

Nisbet, E.G., Dlugokencky, E.J., Bousquet, P., 2014. Methane on the rise-again. Science 343, 493–495.

Northrup, J.M., Anderson, C.R., Wittemyer, G., 2015. Quantifying spatial habitat loss from hydrocarbon development through assessing habitat selection patterns of mule deer. Global Change Biology 21, 3961–3970.

Northrup, J.M., Wittemyer, G., 2012. Characterizing the impacts of emerging energy development on wildlife, with an eye towards mitigation. Ecology Letters 16, 112–125. Available at: https://doi.org/10.1111/ele.12009.

Nugent, D., Sovacool, B.K., 2014. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical meta-survey. Energy Policy 65, 229–244.

Ollerton, J., 2017. Pollinator diversity: distribution, ecological function, and conservation. In: Futuyma, D.J. (Ed.), Annual review of ecology, evolution, and systematics, 48. Annual Reviews, Palo Alto, CA, USA, p. 376 p. 353 & #8722.

Office of Management and Budget (OMB). 2017. 2017 Draft report to Congress on the benefits and costs of federal regulations and agency compliance with the Unfunded Mandates Reform Act. Available at: https://www.whitehouse.gov/wp-content/uploads/2017/12/draft_2017_cost_benefit_report.pdf. Accessed April 10, 2018.

Otto, C.R.V., Roth, C.L., Carlson, B.L., Smart, M.D., 2016. Land-use change reduces habitat suitability for supporting managed honey bee colonies in the Northern Great Plains. PNAS 113, 10430–10435.

Otto, C.R.V., Zheng, H., Gallant, A.L., Iovanna, R., Carlson, B.L., Smart, M.D., Hyberg, S., 2018. Past role and future outlook of the Conservation Reserve Program for supporting honey bees in the Great Plains. PNAS 115, 7629–7634.

Pagel, J.E., Kritz, K.J., Millsap, B.A., Murphy, R.K., Kershner, E.L., Covington, S., 2013. Bald Eagle and Golden Eagle mortalities at wind energy facilities in the contiguous United States. Journal of Raptor Research 47, 311–315. Available at: https://doi.org/10.3356/JRR-12-00019.1.

Pardo, L.H., Blett, T., Clark, C.M., Geiser, L.H., 2015. Impacts of nitrogen pollution on terrestrial ecosystems in the United States. EM: Air and Waste Management Association's Magazine for Environmental Managers 65, 24–30.

Pardo, L.H., Driscoll, C.T., Goodale, C.L., 2011a. Assessment of nitrogen deposition effects and empirical critical loads of nitrogen for ecoregions of the United States. USDA, US Forest Service, Northern Research Station, Newtown Square, PA, USA, pp. 1–7. Available at: https://www.nrs.fs.fed.us/pubs/38109.

Pardo, L.H., Fenn, M.E., Goodale, C.L., Geiser, L.H., Driscoll, C.T., Allen, E.B., Baron, J.S., Bobbink, R., Bowman, W.D., Clark, C.M., Emmett, B., Gilliam, F.S., Greaver, T.L., Hall, S.J., Lilleskov, E.A., Liu, L.L., Lynch, J.A., Nadelhoffer, K.J., Perakis, S.S., Robin-Abbott, M.J., Stoddard, J.L., Weathers, K.C., Dennis, R.L., 2011b. Effects of nitrogen deposition and empirical nitrogen critical loads for ecoregions of the United States. Ecological Applications 21, 3049–3082.

Paschke, M.W., McLendon, T., Redente, E.F., 2000. Nitrogen availability and old-field succession in a shortgrass steppe. Ecosystems 3, 144–158.

Pearse, A.T., Brandt, D.A., Krapu, G.L., 2016. Wintering sandhill crane exposure to wind energy development in the central and southern Great Plains, U.S.A. The Condor 118, 391–401. Available at: https://doi.org/10.1650/condor-15-99.1.

Peischl, J., Karion, A., Sweeney, C., Kort, E.A., Smith, M.L., Brandt, A.R., Yeskoo, T., Aikin, K.C., Conley, S.A., Gvakharia, A., Trainer, M., Wolter, S., Ryerson, T.B., 2016. Quantifying atmospheric methane emissions from oil and natural gas production in the Bakken shale region of North Dakota. Journal of Geophysical Research-Atmospheres 121, 6101–6111.

Perry, L.G., Blumenthal, D.M., Monaco, T.A., Paschke, M.W., Redente, E.F., 2010. Immobilizing nitrogen to control plant invasion. Oecologia 163, 13–24.

Petron, G., Frost, G., Miller, B.R., Hirsch, A.I., Montzka, S.A., Karion, A., Trainer, M., Sweeney, C., Andrews, A.E., Miller, L., Kofler, J., Bar-Ilan, A., Dlugokencky, E.J., Patrick, L., Moore, C.T., Ryerson, T.B., Siso, C., Kolodzey, W., Lang, P.M., Conway, T., Novelli, P., Masarie, K., Hall, B., Guenther, D., Kitzis, D., Miller, J., Welsh, D., Wolfe, D., Neff, W., Tans, P., 2012. Hydrocarbon emissions characterization in the Colorado front range: a pilot study. Journal of Geophysical Research-Atmospheres 117, D04304. Available at: doi:10.1029/2011JD016360.

Pipeline Safety Trust, 2013. PST Pipe Mileage States. Available at:. http://pstrust.org/about-pipelines1/state-by-state-pipeline-information/. Accessed April 14, 2018.

Plumb, R.T., Lautenbach, J.M., Robinson, S.G., Haukos, D.A., Winder, V.L., Hagen, C.A., Sullins, D.S., Pitman, J.C., Dahlgren, D.K., 2019. Lesser prairie-chicken space use in relation to anthropogenic structures. Journal of Wildlife Management 83, 216–230. doi:10.1002/jwmg.21561.

Poessel, S.A., Brandt, J., Mendenhall, L., Braham, M.A., Lanzone, M.J, McGann, A.J., Katzner, T.E., 2018. Flight response to spatial and temporal correlates informs risk from wind turbines to the California Condor. The Condor 120 (2), 330–343. Available at: https://doi.org/10.1650/CONDOR-17-100.1.

Popper, A.N., Smith, M.E., Cott, P.A., Hanna, B.W., MacGillivray, A.O., Austin, M.E., Mann, D.A., 2005. Effects of exposure to seismic airgun use on hearing of three fish species. Journal of the Acoustical Society of America 117, 3958–3971. Available at: https://doi.org/10.1121/1.1904386.

Post van der Burg, M., Symstad, A. J., Igl, L. D., Mushet, D. M., Larson, D. L., Sargeant, G. A., Harper, D. D., Farag, A. M., Tangen, B. A., and Anteau, M. J. 2017. Potential effects of energy development on environmental resources. 41-41. US Geological Survey Scientific Investigations Report 2018-5070-D. Available at: https://doi.org/10.3133/sir20175070D.

Post van der Burg, M., Tangen, B.A., 2015. Monitoring and modeling wetland chloride concentrations in relationship to oil and gas development. Journal of Environmental Management 150, 120–127. Available at: https://doi.org/10.1016/j.jenvman.2014.10.028.

Prach, K., Karesova, P., Jirova, A., Dvorakova, H., Konvalinkova, P., Rehounkova, K., 2015. Do not neglect surroundings in restoration of disturbed sites. Restoration Ecology 23, 310–314.

Prenni, A.J., Day, D.E., Evanoski-Cole, A.R., Sive, B.C., Hecobian, A., Zhou, Y., Gebhart, K.A., Hand, J.L., Sullivan, A.P., Li, Y., Schurman, M.I., Desyaterik, Y., Malm, W.C., Collett, J.L., Schichtel, B.A., 2016. Oil and gas impacts on air quality in federal lands in the Bakken region: an overview of the Bakken Air Quality Study and first results. Atmospheric Chemistry and Physics 16, 1401–1416.

Preston, T.M., 2015. Presence and abundance of non-native plant species associated with recent energy development in the Williston Basin. Environmental Monitoring and Assessment 187, 200. Available at: https://doi.org/10.1007/s10661-015-4408-7.

Preston, T.M., Kim, K., 2016. Land cover changes associated with recent energy development in the Williston Basin; Northern Great Plains, USA. Science of the Total Environment 566, 1511–1518.

Preston, T.M., Chesley-Preston, T.L., 2015. Risk assessment of brine contamination to aquatic resources from energy development in glacial drift deposits: Williston Basin, USA. Science of the Total Environment 508, 534–545.

Preston, T. M., Thamke, J. N., Smith, B. D., and Peterman, Z. E. 2014, Brine contamination of prairie pothole environments at three study sites in the Williston Basin, United States. *In*: Gleason, R. A., Tangen, B. A. [eds.]. Brine contamination to aquatic resources from oil and gas development in the Williston Basin, United States: US Geological Survey Scientific Investigations Report 2014–5017. p. 27–62.

Pruett, C.L., Patten, M.A., Wolfe, D.H., 2009. Avoidance behavior by prairie grouse: implications for development of wind energy. Conservation Biology 23, 1253–1259.

Rabanal, L.I., Kuehl, H.S., Mundry, R., Robbins, M.M., Boesch, C., 2010. Oil prospecting and its impact on large rainforest mammals in Loango National Park, Gabon. Biological Conservation 4, 1017–1024. Available at: https://doi.org/10.1016/j.biocon.2010.01.017.

Ramirez, P., 2010. Bird mortality in oil field wastewater disposal facilities. Environmental Management 46, 820–826.

Rehder, K.J., Stednick, J.D., 2006. Effectiveness of erosion and sediment control practices for forest roads: final report. USDA Forest Service, San Dimas Development and Technology Laboratory, San Dimas, CA, USA, p. 99.

Rella, C.W., Tsai, T.R., Botkin, C.G., Crosson, E.R., Steele, D., 2015. Measuring emissions from oil and natural gas well pads using the mobile flux plane technique. Environmental Science & Technology 49, 4742–4748.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook No. 703. USDA Agricultural Research Service, Washington, DC, USA, p. 404.

Rottler, C.M., Burke, I.C., Palmquist, K.A., Bradford, J.B., Lauenroth, W.K., 2018. Current reclamation practices after oil and gas development do not speed up succession or plant community recovery in big sagebrush ecosystems in Wyoming. Restoration Ecology 26, 114–123.

Sawyer, H., Korfanta, N.M., Nielson, R.M., Monteith, K.L., Strickland, D., 2017. Mule deer and energy development—long-term trends of habituation and abundance. Glob Change Biology 23, 4521–4529. Available at: https://doi.org/10.1111/gcb.13711.

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

Scanlon, B.R., Reedy, R.C., Nicot, J.P., 2014. Comparison of water use for hydraulic fracturing for unconventional oil and gas versus conventional oil. Environmental Science and Technology 48. 12386−12393. Available at: https://doi.org/10.1021/es502506v.

Schlömer, S., Bruckner, T., Fulton, L., Hertwich, E., McKinnon, A., Perczyk, D., Roy, J., Schaeffer, R., Sims, R., Smith, P., Wiser, R., 2014. Annex III: technology-specific cost and performance parameters. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Minx, J.C., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T. (Eds.), Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1329–1356.

Schneider, R.R., Stelfox, B.J., Boutin, S., Wasel, S., 2003. Managing the cumulative impacts of land-uses in the western Canadian sedimentary basin: a modeling approach. Conservation Ecology 7.

Schneider, R.R., Hauer, G., Farr, D., Adamowicz, W.L., Boutin, S., 2011. Achieving conservation when opportunity costs are high: optimizing reserve design in Alberta's Oil Sands Region. PLOS ONE 6 23254−23254.

Schneising, O., Burrows, J.P., Dickerson, R.R., Buchwitz, M., Reuter, M., Bovensmann, H., 2014. Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations. Earths Future 2, 548–558.

Shonkoff, S.B.C., Hays, J., Finkel Madelon, L., 2014. Environmental public health dimensions of shale and tight gas development. Environmental Health Perspectives 122, 787–795.

Schultz, F.D., Mooney, H.A., 1993. Biodiversity and ecosystem function. Springer, Berlin, Germany, p. 525.

Schwarz, J.P., Holloway, J.S., Katic, M.L., Ryerson, T.B., Sweeney, C., Peischl, J., 2015. Black carbon emissions from the Bakken Oil and Gas Development Region. Environmental Science & Technology Letters 2, 281–285.

Shaffer, J.A., Buhl, D.A., 2016. Effects of wind-energy facilities on breeding grassland bird distribution. Conservation Biology 30, 59–71.

Shaffer, J.A., Loesch, C.R., Buhl, D.A., 2019. Estimating offsets for avian displacement effects of anthropogenic impacts. Ecological Applications e01983. doi:10.1002/eap.1983.

Shaffer, J.A., Roth, C.L., Mushet, D.M., 2019. Modeling effects of crop production, energy development and conservation-grassland loss on avian habitat. PLoS ONE 14 (1), e0198382. Available at: https://doi.org/10.1371/journal.pone.0198382.

Shuster, E., Bulling, L., Köppel, J., 2015. Consolidating the state of knowledge—a synoptical review of wind energy's wildlife effects. Environmental Management 56, 300–331.

Simkin, S.M., Allen, E.B., Bowman, W.D., Clark, C.M., Belnap, J., Brooks, M.L., Cade, B.S., Collins, S.L., Geiser, L.H., Gilliam, F.S., Jovan, S.E., Pardo, L.H., Schulz, B.K., Stevens, C.J., Suding, K.N., Throop, H.L., Waller, D.M., 2016. Conditional vulnerability of plant diversity to atmospheric nitrogen deposition across the United States. Proceedings of the National Academy of Sciences of the United States of America 113, 4086–4091.

Sirivedhin, T., Dallbauman, L., 2004. Organic matrix in produced water from the Osage-Skiatook petroleum environmental research site, Osage County, Oklahoma. Chemosphere 57, 463–469.

Skórka, P., Lenda, M., Moroń, D., Kalarus, K., Tryjanowski, P., 2013. Factors affecting road mortality and the suitability of road verges for butterflies. Biological Conservation 159, 148–157. Available at: https://doi.org/10.1016/j.biocon.2012.12.028.

Skórka, P., Lenda, M., Moroń, D., Martyka, R., Tryjanowski, P., Sutherland, W.J., 2015. Biodiversity collision blackspots in Poland—separation causality from stochasticity in roadkills of butterflies. Biological Conservation 187, 154–163. Available at: https://doi.org/10.1016/j.biocon.2015.04.017.

Slonecker, E. T., Milheim, L. E., Roig-Silva, C. M., Malizia, A. R., Marr, D. A., and Fisher, G. B. 2012. Landscape consequences of natural gas extraction in Bradford and Washington Counties, Pennsylvania. 2004-2010 (No. 2012-1154). US Geological Survey.

Smith, S., 2017. Regional native seed cooperatives: working toward available, affordable, and appropriate native seed. Native Plants Journal 18, 126–134.

Smith, G. C., Coulston, J. W., and O'Connell, B. M. 2008. Ozone bio-indicators and forest health: a guide to the evaluation, analysis, and interpretation of the ozone injury data in the Forest Inventory and Analysis Program. Newtown Square, PA, USA: General Technical Report NRS-103, US Forest Service. p. 100.

Smith, G. C., Morin, R. S., and McCaskill, G. L. 2012. Ozone injury to forests across the Northeast and North Central United States, 1994-2010. General Technical Report NRS-103. Newtown Square, PA, USA: US Forest Service. p. 36.

Smith, J.A., Dwyer, J.F., 2016. Avian interactions with renewable energy infrastructure: an update. The Condor: Ornithological Applications 118, 411–423.

Smith, D.R., Snyder, C.D., Hitt, N.P., Young, J.A., Faulkner, S.P., 2012. Shale gas development and brook trout—scaling best management practices to anticipate cumulative effects. Environmental Practice 14, 366–381. Available at: https://doi.org/10.1017/S1466046612000397.

Smith, S.J., Williams, J.R., Menzel, R.G., Coleman, G.A., 1984. Prediction of sediment yield from southern plains grasslands with the modified universal soil loss equation. Journal of Range Management 37, 95–297.

Souther, S., Tingley, M.W., Popesu, V.D., Hayman, D.T.S., Ryan, M.E., Graves, T.A., Hartl, B., Terrell, K., 2014. Biotic impacts of energy development from shale—research priorities and knowledge gaps. Frontiers in Ecology and the Environment 12, 330–338. Available at: https://doi.org/10.1890/130324.

Squillace, M., 2016. Managing unconventional oil and gas development as if communities mattered. Vermont Law Review 40, 525–560.

Stanton, R.L., Morrissey, C.A., Clark, R.G., 2018. Analysis of trends and agricultural drivers of farmland bird declines in North America: a review. Agriculture Ecosystems & Environment 254, 244–254.

Stednick, J.D., Paschke, M.W., Sutherland, P.L., Walker, R.D., Bauder, T.A., 2010. Environmental considerations for coalbed natural gas development in Colorado. In: Reddy, K.J. (Ed.), Coalbed natural gas: Energy and environment. Nova Science Publishers, New York, NY, USA, p. 227 p. 207–227.

Strickland, M.D., Arnett, E.B., Erickson, W.P., Johnson, G.D., Morrison, M.L., Shaffer, J.A., Warren-Hicks, W., 2011. Comprehensive guide to studying wind energy/wildlife interactions. National Wind Coordinating Collaborative, Washington, DC, USA. Available at: https://www.nationalwind.org/comprehensive-guide/.

Sullivan, T.J., 2016. Air Quality Related Values (AQRVs) for Northern Great Plains Network (NGPN) parks: effects from ozone; visibility reducing particles; and atmospheric deposition of acids, nutrients and toxics. Natural Resource Report NPS/NGPN/NRR—2016/1178. National Park Service, Fort Collins, CO, USA. 52 p.

Sun, J.W.C., Narins, P.M., 2005. Anthropogenic sounds differentially affect amphibian call rate. Biological Conservation 212, 419–427.

Sutter, G.C., Davis, S.K., Duncan, D.C., 2000. Grassland songbird abundance along roads and trails in southern Saskatchewan. Journal of Field Ornithology 71, 110–116. Available at: http://www.jstor.org/stable/4514464.

Symstad, A.J., Smith, A.T., Newton, W.E., Knapp, A.K., 2015. Potential nitrogen critical loads for northern Great Plains grassland vegetation. National Park Service, Fort Collins, CO, USA, p. 59.

Tabassum-Abbasi, P.M., Abbasi, T., Abbasi, S.A., 2014. Wind energy: increasing deployment, rising environmental concerns. Renewable and Sustainable Energy Reviews 31, 270–288.

Tessum, C.W., Hill, J.D., Marshall, J.D., 2014. Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. Proceedings of the National Academy of Sciences 111, 18490.

Thamke, J. N., and Craigg, S. D. 1997. Saline-water contamination in Quaternary deposits and the Poplar River, East Poplar Oil Field, northeastern Montana. *US Geological Survey Water-Resource Investigations Report*. 97-4000:42.

Thibault, M., Blaney, S., 2003. The oil industry as an underlying factor in the bushmeat crisis in Central Africa. Conservation Biology 17, 1807–1813.

Thompson, M., Beston, J.A., Etterson, M., Diffendorfer, J.E., Loss, S.R., 2017. Factors associated with bat mortality at wind energy facilities in the United States. Biological Conservation 215, 241–245.

Thompson, S.J., Johnson, D.H., Niemuth, N.D., Ribic, C.A., 2015. Avoidance of unconventional oil wells and roads exacerbates habitat loss for grassland birds in the North American Great Plains. Biology Conservation 192, 82–90.

Thompson, T.M., Shepherd, D., Stacy, A., Barna, M.G., Schichtel, B.A., 2017. Modeling to evaluate contribution of oil and gas emissions to air pollution. Journal of the Air & Waste Management Association 67, 445–461.

Tilman, D., Downing, J.A., 1994. Biodiversity and stability in grasslands. Nature 367, 363–365.

Trail, P.W., 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.

Trainor, A.M., McDonald, R.L., Fargione, J., 2016. Energy sprawl is the largest driver of land use change in United States. PLoS One 11, e0162269. doi:10.1371/journal.pone.0162269.

Trombulak, S.C., Frissell, C.A., 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14, 18–30.

Turner, A.J., Jacob, D.J., Benmergui, J., Wofsy, S.C., Maasakkers, J.D., Butz, A., Hasekamp, O., Biraud, S.C., 2016. A large increase in US methane emissions over the past decade inferred from satellite data and surface observations. Geophysical Research Letters 43, 2218–2224.

Tyner, J.S., Yoder, D.C., Chomicki, B.J., Tyagi, A., 2011. A review of construction site best management practices for erosion control. Transactions of the ASABE 54, 441–450.

US Department of Energy. 2017, 2016. Renewable Energy Data Book, DOE/GO-102016-4904. Available at: https://www.nrel.gov/docs/fy18osti/70231.pdf, Accessed March 27, 2018.

US Department of Justice. 2013. Utility company sentenced in Wyoming for killing protected birds at wind projects, Friday, November 22, 2013 Press Release. Available at: https://www.justice.gov/opa/pr/utility-company-sentenced-wyoming-killing-protected-birds-wind-projects. Accessed April 2, 2018.

Uselman, S.M., Snyder, K.A., Leger, E.A., Duke, S.E., 2015. Emergence and early survival of early versus late seral species in Great Basin restoration in two different soil types. Applied Vegetation Science 18, 624–636.

Van Wilgenburg, S.L., Hobson, K.A., Bayne, E.M., Koper, N., 2013. Estimated avian nest loss associated with oil and gas exploration and extraction in the Western Canadian Sedimentary Basin. Avian Conservation and Ecology 8 (2), 9.

Vautard, R., Thais, F., Tobin, I., Bréon, F.M., De Lavergne, J.G.D., Colette, A., Yiou, P., Ruti, P.M., 2014. Regional climate model simulations indicate limited climatic impacts by operational and planned European wind farms. Nature Communications 5, 3196.

Vengosh, A., Jackson, R. B., Warner, N., Darrah, T. H., and Kondash, A. 2014. A critical review of the risks to water resources from unconventional shale gas. Environmental Science and Technology 48:8334−8348.

Wagg, C., O'Brien, M.J., Vogel, A., Scherer-Lorenzen, M., Eisenhauer, N., Schmid, B., Weigelt, A., 2017. Plant diversity maintains long-term ecosystem productivity under frequent drought by increasing short-term variation. Ecology 98, 2952–2961.

Wallace, Z.P., Kennedy, P.L., Squires, J.R., Olson, L.E., Oakleaf, R.J., 2016. Human-made structures, vegetation, and weather influence ferruginous hawk breeding performance. Journal of Wildlife Management 80, 78–90. Available at: https://doi.org/10.1002/jwmg.1000.

Wedin, D.A., Tilman, D., 1996. Influence of nitrogen loading and species composition on the carbon balance of grasslands. Science 274, 1720–1723.

Weiss-Penzias, P.S., Gay, D.A., Brigham, M.E., Parsons, M.T., Gustin, M.S., ter Schure, A., 2016. Trends in mercury wet deposition and mercury air concentrations across the US and Canada. Science of the Total Environment 568, 546–556.

Weyant, C.L., Shepson, P.B., Subramanian, R., Cambaliza, M.O.L., Heimburger, A., McCabe, D., Baum, E., Stirm, B.H., Bond, T.C., 2016. Black carbon emissions from associated natural gas flaring. Environmental Science & Technology 50, 2075–2081.

Wiese, F.K., Montevecchi, W.A., Davoren, G.K., Huettmann, F., Diamond, A.W., Linke, J., 2001. Seabirds at risk around offshore oil platforms in the north-west Atlantic. Marine Pollution Bulletin 42, 1285–1290.

Winder, V.L., McNew, L.B., Gregory, A.J., Hunt, L.M., Wisely, S.M., Sandercock, B.K., 2014a. Effects of wind energy development on the survival of Greater Prairie-Chickens. Journal of Applied Ecology 51, 395–405.

Winder, V.L., McNew, L.B., Gregory, A.J., Hunt, L.M., Wisely, S.M., Sandercock, B.K., 2014b. Space use by female Greater Prairie-Chickens in response to wind energy development. Ecosphere 5 (art3).

Winder, V.L., Gregory, A.J., McNew, L.B., Sandercock, B.K., 2015. Responses of male Greater Prairie-Chickens to wind energy development. The Condor: Ornithological Applications 117, 284–296. Available at: https://doi.org/10.1650/CONDOR-14-98.1.

Wimberly, M.C., Janssen, L.L., Hennessy, D.A., Luri, M., Chowdhury, N.M., Feng, H., 2017. Cropland expansion and grassland loss in the eastern Dakotas: new insights from a farm-level survey. Land Use Policy 63, 160–173.

Wulff, S.J., Butler, M.J., Ballard, W.B., 2016. Assessment of diurnal wind turbine collision risk for grassland birds on the southern Great Plains. Journal of Fish and Wildlife Management 7, 129–140. doi:10.3996/042015-JFWM-031.

Wright, C.K., Wimberly, M.C., 2013. Recent land use change in the Western Corn Belt threatens grasslands and wetlands. Proceedings National Academy Science 110, 4134–4139.

Xu, Y., Li, J., Tan, Q., Peters, A.L., Yang, C., 2018. Global status of recycling waste solar panels: a review. Waste Management 75, 450–458.

Zayas, J., Derby, M., Gilman, P., Ananthan, S., 2015. Enabling wind power nationwide (No. DOE/EE-1218). US Department of Energy, Washington, DC, USA.

Zelenak, J.R., Rotella, J.J., 1997. Nest success and productivity of ferruginous hawks in northern Montana. Canadian Journal of Zoology 75, 1035–1041. Available at: https://doi.org/10.1139/z97-124.

Zhang, Y.X., Jacob, D.J., Horowitz, H.M., Chen, L., Amos, H.M., Krabbenhoft, D.P., Slemr, F., St Louis, V.L., Sunderland, E.M., 2016. Observed decrease in atmospheric mercury explained by global decline in anthropogenic emissions. Proceedings of the National Academy of Sciences of the United States of America 113, 526–531.

Zhou, L., Tian, Y., Baidya, R.S., Thorncroft, C., Bosart, L.F., Hu, Y., 2012. Natural Climate Change 2, 539–543.

Zimmerling, J.R., Pomeroy, A.C., d'Entremont, M.V., Francis, C.M., 2013. Canadian estimate of bird mortality due to collisions and direct habitat loss associated with wind turbine developments. Avian Conservation and Ecology 8, 10.