ECOLOGY LETTERS

Ecology Letters, (2013) **16**: 112–125 doi: 10.1111/ele.12009

REVIEW AND SYNTHESIS

Characterising the impacts of emerging energy development on wildlife, with an eye towards mitigation

Joseph M. Northrup,* and George Wittemyer

Department of Fish, Wildlife, and Conservation Biology, Colorado State University, Campus Delivery 1474 Fort Collins, CO 80523, USA

**Correspondence: E-mail: joe.northrup@colostate.edu*

Abstract

Global demand for energy is projected to increase by 40% in the next 20 years, and largely will be met with alternative and unconventional sources. Development of these resources causes novel disturbances that strongly impact terrestrial ecosystems and wildlife. To effectively position ecologists to address this prevalent conservation challenge, we reviewed the literature on the ecological ramifications of this dominant driver of global land-use change, consolidated results for its mitigation and highlighted knowledge gaps. Impacts varied widely, underscoring the importance of area and species-specific studies. The most commonly reported impacts included behavioural responses and direct mortality. Examinations of mitigation were limited, but common easements included (1) reduction of the development footprint and human activity, (2) maintenance of undeveloped, 'refuge' habitat and (3) alteration of activity during sensitive periods. Problematically, the literature was primarily retrospective, focused on few species, countries, and ecoregions, and fraught with generalisations from weak inference. We advocate future studies take a comprehensive approach incorporating a mechanistic understanding of the interplay between development-caused impacts and species ecology that will enable effective mitigation. Key areas for future research vital to securing a sustainable energy future in the face of development-related global change are outlined.

Keywords

Alternative energy, best management practices, conservation, energy extraction, industrial development, land conversion, renewable energy, wilderness.

Ecology Letters (2013) **16**: 112–125

INTRODUCTION–RAMIFICATIONS OF THE NEW ENERGY FUTURE

Global demand for energy is projected to increase by 40% in the next 20 years (International Energy Agency 2009). With the potential peak in world conventional oil production (Kerr 2011), rising oil prices (Erturk 2011), and concerns over greenhouse gas emissions and subsequent climate change (Intergovernmental Panel on Climate Change 2007), energy demand increasingly will be met with alternative and unconventional (e.g. gas shale, oil sands) energy sources. The numerous economic and societal benefits of alternative and unconventional domestic energy production (e.g. job creation, national security), technological advancements such as hydraulic fracturing (United States Energy Information Administration 2010; Kerr 2010) and directives and legislative mandates for renewable energy (United States Energy Information Administration 2008; European Commission 2009) have spurred a rapid increase in global alternative and unconventional energy production over the last decade (International Energy Agency 2009; United States Energy Information Administration 2010). This production, and related development, is poised to continue its upward trajectory (International Energy Agency 2009), with over 200 000 km^2 of new land projected to be developed in the US alone by 2035 (McDonald *et al.* 2009). From an ecological perspective, development can cause large-scale and novel alterations to ecosystems, resulting in habitat loss and fragmentation (Leu *et al.* 2008; McDonald *et al.* 2009) that strongly impact terrestrial wildlife populations and their ecosystems. In light of the new energy future, understanding and mitigating the impacts of energy development will be one of the major global challenges for ecologists in the coming decade.

The potential environmental effects of energy development (e.g. water contamination, deforestation, climate change) garner much public interest and engender important debates. It is critical that the impacts of development to wildlife are part of this conversation and that the best knowledge on this issue is available to decision makers. As such, there is an explicit need to summarise and synthesise the current literature on the impacts to wildlife in order to (1) characterise the type of development-caused environmental risks to wildlife, (2) understand general patterns of wildlife responses, (3) summarise results that offer guidance for mitigating impacts through onsite mitigation and best management practices (BMPs; i.e. measures employed by industry that reduce environmental impacts), and (4) highlight the need for such information where it is lacking. To this end, we reviewed the literature on recent energy development and development mitigation throughout the world. For the US and Canada, where the majority of such research was focused, we quantified and summarised impacted species, the geographical location and ecoregions where research on impacts took place, and the robustness of study designs in terms of informing mitigation measures.

IMPACTS OF EMERGING ENERGY SECTORS TO WILDLIFE

Five energy sectors have driven the global increase in energy development: unconventional oil and gas, wind, bioenergy (including biofuels and biomass electricity production), solar and geothermal energy (International Energy Agency 2009; United States Energy Information Administration 2010). These sectors differ in their geographical locations, spatial extent and impacts to wildlife, and thus have received various levels of attention in the literature. We conducted a systematic review of the global literature on the impacts of the above energy sectors to terrestrial wildlife (see Appendix S1 for a detailed description of the review protocol and resulting literature). We focused on empirical studies or meta-analyses that examined wildlife impacts relative to these sectors, while excluding model-based simulation studies. We did not review impacts from conventional oil development, as this type of development has been ongoing for several decades and is on the decline (United States Energy Information Administration 2010). Finally, we used detailed information from studies specific to the US and Canada for direct quantification of impacts to species as well as the geographical locations and ecoregions impacted (the latter for the US alone). These focal countries dominated the published literature (> 70% of reviewed studies; Appendix S1), hold major reserves of unconventional oil and natural gas and substantial potential for renewable energy (Lu *et al.* 2009; World Energy Council 2010, 2012; Dinçer 2011), are two of the largest global producers (Table 1), and have publicly available information on energy production and potential. The US and Canada are also on the forefront of developing cutting-edge production methods (e.g. hydraulic fracturing) that are likely to expand into other regions. Thus, the energy development and subsequent environmental impacts in these countries reflect the current, and likely future, global trends in development (International Energy Agency 2009).

Wind

While the debate on environmental impacts of many energy sectors has focused on carbon emissions or pollutants, the primary impact of wind energy has been to wildlife. The most common impact of this sector was the direct mortality of bats and birds from collisions with wind turbines (Table 2; Kunz *et al.* 2007; Kuvlesky *et al.* 2007; Rydell *et al.* 2010). The spatial distribution of studies in the reviewed literature was limited, focusing on the US, Canada or Western Europe despite substantial global potential and interest (Lu *et al.* 2009; Table 1). In the US and Canada, the population repercussions of this mortality source were of greatest concern for bats due to the magnitude of such mortality, and the lack of information on demography and population sizes (Kuvlesky *et al.* 2007). Most mortalities in this region were of migratory, tree-dwelling bats (Kunz *et al.* 2007; Appendix S1). The patterns of mortality in Europe stood in contrast to the US and Canada, as migratory and non-migratory bats were killed in similar proportions, and the species for which mortalities were most common were generally thought to have stable populations (Rydell *et al.* 2010). Despite these differences, the underlying mechanisms for these mortalities appeared to be similar between the two continents and included bats engaging in behaviours that make them more susceptible to collisions, or being attracted to turbines for roosting or foraging. In general, these proximate causes for collisions remained untested, but the ultimate driver appeared to be that wind farms were located in high-use areas (Kunz *et al.* 2007; Rydell *et al.* 2010).

As with bats, siting of wind farms in areas actively used by birds (e.g. flyways) was a major driver of mortalities (Kuvlesky *et al.* 2007). In North America, fewer birds (relative to bats) were killed due to collisions with turbines, and population-level consequences have not been documented (Kuvlesky *et al.* 2007), while in Europe wind turbine collisions likely have contributed to the decline of some species (e.g. the Egyptian vulture (*Neophron percnopterus*); Carrete *et al.* 2009), and impacted breeding success and fecundity of others (e.g. the griffon vulture (*Gyps fulvus*) and the white-tailed eagle (*Haliaeetus albicilla*); Dahl *et al.* 2012; Martinez-Abrain *et al.* 2012). On both continents, wind farms negatively impacted bird abundance and elicited behavioural responses (e.g. avoidance), although this impact was species and site dependent (de Lucas *et al.* 2004; Stewart *et al.* 2007; Pearce-Higgins *et al.* 2009; Garvin *et al.* 2011; Appendix S1).

Aside from bats and birds, we found only six studies that examined impacts of wind energy on terrestrial wildlife (two on ungulates, three on desert tortoises (*Gopherus agassizii*) and one on ground squirrels (*Spermophilus beecheyi*); see Appendix S1 for citations). Ungu-

Table 1 Energy produced by region from five unconventional or alternative energy sectors [bioenergy (biofuels and biomass electricity), wind, solar, geothermal and unconventional oil] number of countries in each region, number of countries producing energy for each sector and number of countries with studies on the impacts of bioenergy and wind energy development on wildlife*

Region (no. of countries)	Wind† (no. countries producing)	No. countries with studies; wind	Biofuels‡; biomass electricity† (no. countries producing)	No. countries with studies; bioenergy	Solar† (no. countries producing)	Geothermal‡ (no. countries producing)	Shale oil§; other unconventional oil¶ (no. countries producing)
Africa (56)	1.96 (8)	0	0.99; 1.47 (13)	0	0.04 (8)	1.52 (1)	0; 0 (0)
Asia and Oceania (46)	78.75 (20)	0	99.21; 37.94 (19)	2	4.42 (19)	26.59 (7)	375; 24 (2)
Central and South America (44)	3.29 (20)	0	588.25; 36.79 (22)	1	0.001 (6)	3.16 (5)	200; 14778 (5)
Eurasia (16)	0.62 (8)	0	4.36; 3.56 (5)	0	<0.001 (1)	0.44 (1)	355; 773 (3)
Europe (40)	142.44 (27)	8	248.31; 137.32 (29)	4	21.98 (31)	10.22 (7)	0; 1191 (3)
Middle East (14)	0.26 (4)	0	0.1; 0.05 (2)	0	0.43 (2)	0 (0)	0; 0 (0)
North America (6)	100.52 (3)	2	914.42; 77.04 (3)	2	1.44 (3)	21.95 (3)	0; 6645 (3)

*No studies were found examining the impacts of solar and geothermal energy development to wildlife. Unconventional oil studies were not quantified because the source (i.e. conventional vs. unconventional) was not determinable from global studies (see Appendix S1). Information on unconventional natural gas production was not available globally.

†Billion kilowatt hours produced. Data obtained from the US Energy Information Administration (http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm).

‡Thousand barrels per day produced. Data obtained from the US Energy Information Administration (http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm).

§Thousand tons produced. Data obtained from World Energy Council (2010).

¶Million barrels produced. Data obtained from World Energy Council (2010).

Table 2 For each energy development sector, the identified and hypothesised (likely) impacts to wildlife, suggested best management practices (BMPs) and on-site mitigation measures for reducing impacts, and suggested research needs. Identified impacts and suggested BMPS and on-site mitigation measures are listed in order of their frequency in the reviewed literature

Sector	Identified impacts	Likely impacts	BMPs and on-site mitigation measures	Research needs
Wind	Direct mortality Altered behaviour and displacement Decreased fecundity Decreased breeding success Acoustic masking	Altered species composition	Avoid siting near bat colonies or in habitat used for nesting, migration, foraging, soaring for large birds, or other activities that may encourage collisions Curtailment during sensitive seasons, times of high insect activity (bats), low wind (bats), high wind (birds), clear weather and immediately after sunset (bats), and when threatened species are present (birds) Increase cut-in speed Replace older towers (birds) Removal of towers with high mortality rate Move known anthropogenic food sources (scavenging birds) Install shorter towers for bats and fewer, larger towers for birds Habitat offsets (birds) Deploy echolocation devices during assessments Pre-development assessment	Behavioural impacts Economic analyses to optimise cut-in speed and stoppage times Population and demographic information for bats (US and Canada) Greater geographical breadth of bird research Further research into reasons for collisions
Bioenergy	Decreased species richness, diversity and abundance Altered species composition Increased invasive species Large-scale deforestation Altered space-use patterns	Declining populations	Plant native species or high-diversity polycultures Maintain mosaic of harvested and unharvested land Maintain native habitat in proximity to crops Harvest after fledging of bird nestlings Harvest to maintain structural diversity in vegetation Plant woody crops that support nesting habitat Plant larger woody crop plots Plant on degraded or already cultivated lands Promote understory vegetation (epiphytes in oil palm plantations; weeds in herbaceous crops) Habitat offsets Create piles or windrows of coarse woody debris	Research on impacts to a greater diversity of species Research on global impacts of bioenergy production in North America Focused research on dedicated bioenergy crops
Unconventional oil and natural gas	Altered behaviour, movement, home ranges and territories Altered reproduction Altered species composition Acoustic masking Declining populations Decreased survival Direct mortality Reduced abundance Increased stress Increased hunting pressure	Loss of migratory routes Increased predation Increased illegal hunting	Restricted development in and around critical habitat Maintenance of refuge habitat Re-vegetation and habitat enhancements Traffic and access restrictions Narrow seismic lines Siting of developments in areas obscured by vegetation or topography Noise suppression and barriers Clustered development Helicopter assisted or remote development Habitat offsets Directional drilling Setback distances from critical habitat Remote liquid gathering systems Install predator deterrents around developments Liberal harvest of primary prey Remotely activated deterrents Increased pipeline height Pre-development assessment	Assessments of impacts to migratory routes Identification of thresholds above which demographic and population-level impacts occur Untangling of response to multiple activities Noise mitigation methods

(continued)

Table 2. (continued)

Sector	Identified impacts	Likely impacts	BMPs and on-site mitigation measures	Research needs
Solar		Displacement Altered behaviour Altered species composition Loss of migratory routes	Pre-development assessment	Basic research on impacts to wildlife
Geothermal		Displacement Altered behaviour Altered species composition	Pre-development assessment	Basic research on impacts to wildlife

lates in these studies showed no behavioural responses to wind energy. Likewise tortoises showed no population-level response, but mortality related to culverts in wind energy facilities was hypothesised to be a potentially significant source of mortality. Ground squirrels showed behavioural alteration likely due to acoustic masking from wind turbines.

Bioenergy

The debate over the environmental impacts of bioenergy has centred on carbon emissions and deforestation, but the cultivation of crops used in this sector can elicit large-scale land-use change with implications for wildlife (Fargione *et al.* 2010). Importantly, bioenergy production occurs on all continents, but the literature on the impacts to wildlife is limited to only a few countries (e.g. the US, UK and Indonesia; Table 1). This literature can be categorised by the nature of land conversion required for bioenergy cultivation. In temperate regions, where we only found studies from the US, Canada and the UK, herbaceous crops [e.g. corn or miscanthus (*Miscanthus giganteus*)] and short-rotation woody crops [e.g. poplar (*Populus* spp.) or willow (*Salix* spp.)] were typically cultivated on lands that already have been converted for agricultural purposes (although in the US some of these lands have been reclaimed; i.e. through the Conservation Reserve Program). In tropical regions, crops such as oil palm (*Elaeis guineensis*) and sugarcane (*Saccharum* spp.) were harvested as biodiesel feedstocks and often required land conversion from primary or secondary native forests. While cultivation of these crops occurred in a number of countries, we only found studies from Borneo, Malaysia and Guatemala (Appendix S1).

The environmental impacts of oil palm cultivation have become a global conservation issue in the last decade (Fitzherbert *et al.* 2008). Oil palm cultivation and its associated deforestation represent one of the greatest threats to biodiversity in some tropical countries (Koh *et al.* 2011). Literature on the direct impacts to wildlife largely focused on bird diversity, with oil palm plantations having substantially lower diversity and disproportionately lower numbers of sensitive and rare species than non-palm forests (Fitzherbert *et al.* 2008; Danielsen *et al.* 2009; Edwards *et al.* 2010). The degree of biodiversity loss depended on the proximity of plantations to intact native forest or forest fragments (Koh 2008) and likely was related to lower vegetative diversity and limited food resources in plantations. Most research on the impacts of bioenergy production from oil palm to wildlife was from southeast Asia, but oil palm could be grown throughout the tropics, with similar conservation implications (Butler & Laurance 2009). Similar to oil palm, the production of biodiesel from sugarcane or soy (*Glycine* sp.) contributed, along with other factors, to land clearing in the Amazon (Nepstad *et al.* 2008). While empirical research on the direct impacts to wildlife in this area was lacking, large-scale deforestation will impact a host of species across numerous taxonomic groups. Critically, deforestation of the Amazon was not only a result of local demand for bioenergy but influenced by global markets. Increased production of bioenergy from corn in the US was linked to raising prices for soy, and thus further Amazonian land clearing for production of this crop (Laurance 2007).

In temperate regions, the most commonly documented impacts of herbaceous bioenergy crops were lower songbird and small mammal species richness, diversity, and abundance relative to reference areas (e.g. field margins or undisturbed grasslands; Semere & Slater 2007; Sage *et al.* 2010; Riffell *et al.* 2011; Robertson *et al.* 2011a,b). These patterns, however, depended on the surrounding land use (Bellamy *et al.* 2009). Furthermore, if bioenergy crops composed only a small proportion of the landscape, an increase in species richness could result (Meehan *et al.* 2010) through increased habitat heterogeneity (Roth *et al.* 2005; Robertson *et al.* 2011a). In some areas, bioenergy crops such as corn provided high-quality forage for large herbivores; thus, cultivation was hypothesised to alter space-use of these animals (Walter *et al.* 2009).

Short-rotation woody crops, planted in temperate regions, increased nesting habitat for birds in some areas and enhanced species diversity and abundance for birds, mammals and some reptiles relative to undisturbed forest, but potentially decreased amphibian diversity and abundance (Berg 2002; Sage *et al.* 2006; Dhondt *et al.* 2007; see Appendix S1). For birds, the understory vegetation in woody bioenergy crops provided an important food source (Fry & Slater 2011). Again, these impacts depended on the surrounding habitat and the type of land that was converted for energy development. The largest body of research on impacts of woody bioenergy crops to wildlife was from the UK, where historically much of the land was converted to farmland. Thus, these impacts may not apply for areas where cultivation occurs at the expense of natural habitat.

As with other energy sectors, the impacts of bioenergy crops differed by species, and therefore, their cultivation led to altered species composition (Roth *et al.* 2005; Riffell *et al.* 2011). Specific responses varied by crop, land type, (Berg 2002; Tilman *et al.* 2006; Semere & Slater 2007; Meehan *et al.* 2010; Robertson *et al.* 2011a) and harvest practices (Roth *et al.* 2005), and depended on the remaining habitat within crops or plantations (Koh 2008). These impacts were of greatest conservation concern when crops or plantations replaced native forests, crop margins or lands in conservation holdings (Riffell *et al.* 2011). Such conversion is likely to become more common with greater economic incentives for bioenergy crop cultivation. Another major concern with herbaceous and woody bioenergy production was the potential for crops to become invasive species. Many prospective bioenergy crops have similar characteristics to successful invasive species (e.g. rapid growth with little chemical or nutrient input) and were more likely to become invasive than reference plants (Buddenhagen *et al.* 2009). For wildlife, such invasions are likely to act synergistically with other bioenergy impacts.

Unconventional oil and gas

Unconventional oil or natural gas reserves exist on every continent, and their development is set to become a major energy sector worldwide (World Energy Council 2010, 2012). Information on global production of unconventional natural gas and assessments of reserves, however, is noticeably lacking at this time, while unconventional oil extraction currently occurs in few countries (Table 1). The US and Canada produce the greatest amount of unconventional oil and natural gas energy globally (United States Energy Information Administration 2010; World Energy Council 2012), and reflectively, the related literature was predominantly concentrated on these countries (Appendix S1). With development likely to increase globally in coming years, the impacts documented in this region are salient globally.

Development of unconventional oil and natural gas broadly impacted wildlife by (1) fragmentation through the creation of complex road and pipeline networks, (2) direct habitat conversion from the development footprint, (3) eliciting behavioural responses, particularly avoidance, due to development-related activity (construction, increased human activities and anthropogenic noise), and (4) inviting further fragmentation, resource extraction and direct mortality of wildlife through increased human access to wild lands. Globally, studies mainly focused on impacts to large mammals. Importantly, we note that global studies did not distinguish between conventional and unconventional development, and therefore, we limited our review to a select group of key studies outside the US and Canada (see Appendix S1 for detailed discussion of evaluation protocols). In the US and Canada, most studies documented negative impacts of unconventional oil and natural gas development to wildlife (Fig. 1). Studies of these impacts focused mainly on ungulates, greater sage grouse (*Centrocercus urophasianus*), and a variety of song bird species.

The impacts of unconventional oil and gas development on ungulates and other large mammals were well characterised due to the economic and conservation importance of these species. For large mammals, behavioural impacts were most commonly documented and included large-scale displacement from developed areas and around development infrastructure (Sawyer *et al.* 2006), altered movement or home range patterns (Dyer *et al.* 2002), and more fine-scale behavioural modifications likely in response to variable human activity, traffic or disturbance from seismic exploration (Dyer *et al.* 2002; Sawyer *et al.* 2009a; Wrege *et al.* 2010; Wasser *et al.* 2011). These responses varied by spatial scale and across species, and not all large mammals were impacted by development infrastructure (Kolowski & Alonso 2010; Rabanal *et al.* 2010).

Few studies documented population-level impacts for specific species of large mammal from development, although oil and natural gas extraction likely has influenced population declines of caribou (*Rangifer* spp.; Sorensen *et al.* 2008; Wasser *et al.* 2011), led to decreased survival of elk (*Cervus elaphus*; Dzialak *et al.* 2011), and contributed to heightened grizzly bear (*Ursus arctos*) mortality (Nielsen *et al.* 2006). One study documented increased nutritional and psychological stress of caribou, likely in response to human activity related to oil and natural gas development (Wasser *et al.* 2011). While direct population-level impacts from this sector were infrequently documented, in Africa development contributed to unsustainable levels of bushmeat extraction due to increased human presence (Thibault & Blaney 2003), and any increases in development that may accompany unconventional oil and gas development are likely to exacerbate this situation. Impacts of oil and gas development on the migrations of large mammals have not been rigorously examined, but it is likely that migrations of some individuals will be disrupted by development (Sawyer *et al.* 2009b). Finally, altered behavioural patterns could lead to increased vulnerability to predators for certain species.

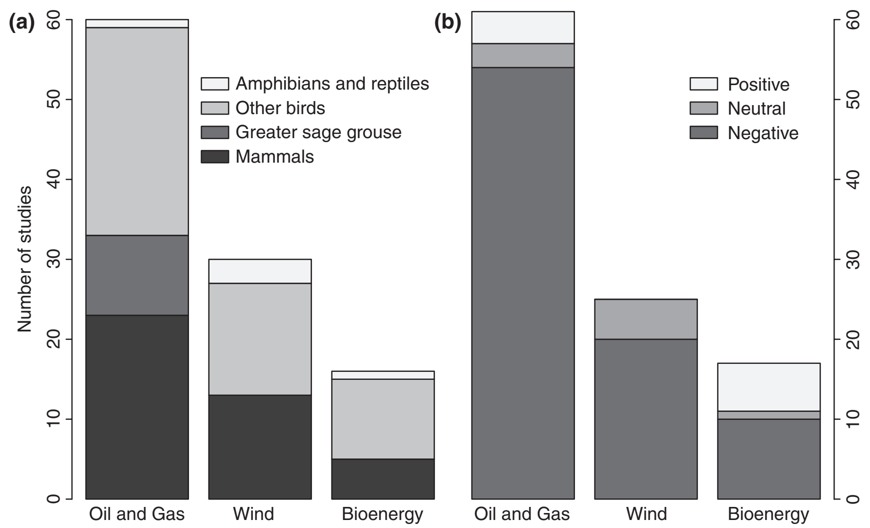

Figure 1 Number of US- and Canada-focused studies summarised by (a) taxonomic group and energy sector and (b) whether they documented negative, neutral or positive responses by wildlife. Several studies focused on multiple species or treatments (e.g. bioenergy crop type) and thus could have multiple responses.

For bird species, the most common impact of oil and gas development was reduced abundance around development infrastructure (Pitman *et al.* 2005; Jarnevich & Laubhan 2011). Such impacts often were species-specific, leading to alterations in species composition in developed areas (Bayne *et al.* 2008; Gilbert & Chalfoun 2011). Anthropogenic noise produced from oil and gas extraction also altered species composition (Bayne *et al.* 2008; Francis *et al.* 2011; Appendix S1), which indirectly influenced plant pollination and seed dispersal (Francis *et al.* 2012). Such noise affected reproductive parameters such as mate pairing success, age distribution, and nesting frequency and abundance (Francis *et al.* 2011; Appendix S1). Noise also caused birds to alter their song characteristics, which can exacerbate negative impacts and potentially increased predatory exposure (Francis *et al.* 2011; Appendix S1). Other, less commonly reported impacts from unconventional oil and natural gas development included changes in songbird territory size and shape due to habitat alteration from seismic exploration (Machtans 2006; Appendix S1), and direct mortality or contamination from landing on wastewater ponds produced from oil and gas drilling and oil sands extraction, or ingesting toxicants therein (Gurney *et al.* 2005; Ramirez 2010). Seismic exploration and wastewater ponds accompany almost any development project in this sector, so such impacts likely were more widespread than suggested by the literature. While there was little research on the impacts of oil and gas development to bird species outside of the US and Canada, the creation of development-related roads and other linear features in the tropics will likely hasten human-caused deforestation and colonisation of forested areas (Laurance *et al.* 2009).

While specific only to the US and Canada, impacts of energy development on sage grouse were possibly the best characterised due to their conservation status (listed as warranted but precluded under the Endangered Species Act in the US and endangered under Canada's Species at Risk Act) and overlap with significant unconventional natural gas reserves. Research on the response of sage grouse to energy development primarily was focused on understanding the reasons for population declines. Numerous studies documented impacts that directly affect sage grouse reproductive output in developed areas, including lower frequency of nest initiation (Lyon & Anderson 2003), greater probability of brood loss (Aldridge & Boyce 2007) and lower recruitment of juveniles to leks (Holloran *et al.* 2010). In addition, sage grouse had decreased lek attendance (a metric used to monitor populations; Doherty *et al.* 2010) and lower survival probability (Holloran *et al.* 2010) in developed areas. Sage grouse also avoided areas around developments (Doherty *et al.* 2008). These impacts likely were exacerbated by the fact that development decreased available grouse habitat, while increasing habitat for predators (Bui *et al.* 2010) and mosquitoes carrying West Nile virus (Zou *et al.* 2006), to which grouse are susceptible. Regulations were in place to provide protection for sage grouse in areas being actively developed for natural gas, although these regulations likely were insufficient (Doherty *et al.* 2008).

Studies on the impacts of unconventional oil and gas development on species other than birds and large mammals were limited (Fig. 1). We found only one study examining the influence of oil and gas development on amphibians or reptiles with no documented response (see Appendix S1).

Solar and geothermal

We found no empirical peer-reviewed research on the impacts of either solar or geothermal energy development on wildlife. These sectors also are the least developed globally (Table 1). Lovich & Ennen (2011) reviewed the available literature (mostly from unpublished reports) and hypothesised that habitat loss and fragmentation and microclimate alteration around solar arrays were the most likely impacts to wildlife (Table 2). The desert southwest of the US holds some of the greatest potential for solar energy in the US and Canada; thus, wildlife in this area faces the greatest threat (Table 3; Lovich &

Table 3 Top five ecoregions with greatest potential for energy development, by sector, for the continental US. Ecoregions less than 100 km^2 were excluded. Area values indicate total ecoregion area (km^2) in the continental US. See Appendix S2 for methodology

Rank	Unconventional oil and gas (per cent overlapped by basins; area km^2)	Wind (per cent in wind power classes 5 and 6; area km^2)*	Bioenergy (mean tons/ km^2/year; area km^2)	Solar (mean kWh potential; area km^2)	Geothermal (per cent in classes 1 and 2; area km^2)†
1	Allegheny Highlands forests (100%; 101 492)	Cascade Mountains leeward forest (93%; 16, 236)	Central tall grasslands (166.83; 259 845)	Mojave desert (7470; 131 271)	Eastern Cascades forests (84%; 56 208)
2	Western Gulf coastal grasslands (100%; 78 295)	South Central Rockies forests (85%; 159 790)	Willamette Valley forests (156.20; 15 201)	Sonoran Desert (7271; 116 759)	Sierra Madre Occidental pine-oak forests (84%; 7, 267)
3	East Central Texas forests (100%; 55 067)	British Columbia mainland coastal forests (78%; 14 611)	Central Pacific coastal forests (151.53; 41 855)	Sierra Madre Occidental pine-oak forest (7170; 7267)	Snake-Columbia shrub steppe (82%; 220 029)
4	Mississippi lowland forests (99%; 121 921)	Wasatch and Uinta montane forests (70%; 41, 481)	Puget lowland forests (126.93, 15 579)	Arizona mountain forests (7032; 109 135)	Colorado Rockies forests (80%; 133 295)
5	Tamaulipan mezquital (99%, 59 906)	Colorado Rockies forests (68%; 133 295)	Mississippi lowland forests (126.87; 121, 921)	Colorado plateau shrublands (6777; 326 767)	Great Basin shrub steppe (75%; 337 545)

*Power class descriptions obtained from National Renewable Energy Lab (http://www.nrel.gov/gis/data_wind.html): (5) 7.5–8.0 m/s (excellent potential); (6) 8.0–8.8 m/s (outstanding potential).

†Class descriptions obtained from National Renewable Energy Lab (http://www.nrel.gov/gis/data_geothermal.html) and describe geothermal energy potential with classes 1 and 2 being the most favourable.

Ennen 2011). Similar to other sectors, the location of solar arrays relative to wildlife migration routes and critical habitat figures to be important in dictating the conservation implications (Lovich & Ennen 2011).

Geothermal energy development can involve the emission of pollutants (Pimental 2008) and will involve habitat alteration and related impacts, at least at a small scale (Table 2). Literature on empirical studies regarding impacts from this sector was lacking globally. The majority of geothermal energy potential in the US and Canada lays in the west and southwest of the US (Table 3; Appendix S2).

Summary, general patterns and research needs

The impacts of energy development to wildlife varied among species and sectors (Table 2). In our quantification of studies from the US and Canada, most studies documented negative impacts (Fig. 1). Behavioural alterations in response to development were the most common impact reported and likely precede demographic or population-level consequences. Behavioural responses included large-scale displacement, as well as more nuanced changes to habitat selection and movement patterns related to habitat fragmentation. Fragmentation is an unavoidable by-product of development, potentially resulting in both the loss of migratory routes and decreased connectivity within and between populations, as well as further impacts related to human access to wild lands. The preponderance of behavioural alterations may have resulted from the large body of research on unconventional oil and gas development in the US and Canada, for which behavioural responses were typical, or due to a disproportionate number of studies in this sector focused on behavioural impacts over other factors. Broadly, across studies in different regions, results demonstrated wide variation in the response of species to the same or similar disturbance, thus altered species composition and interactions appear to be a likely outcome of any development project. While less common, the impacts with the most direct conservation implications included those that caused decreased survival, altered reproduction and population declines. These impacts were documented for some species in response to unconventional oil and natural gas development and wind energy but were undocumented in other sectors, probably reflecting limited research.

While the literature on impacts of unconventional and alternative energy development to wildlife has initiated important discussion and further research, a number of major shortcomings exist and must be addressed. Importantly, the literature was severely limited geographically, both globally (Table 1) and in the US and Canada (Fig. 2). In many cases, research on impacts in the US and Canada did not overlap the ecoregions with the greatest potential for development (Olson *et al.* 2001; Table 3; see also Appendix S2), and similar patterns likely exist worldwide. Such ecoregions and the component species are potentially at the greatest risk but severely understudied (see Appendix S2). In addition, the literature was focused on few species (Fig. 1), and the majority of studies were retrospective (less than 20% of the reviewed studies from the US and Canada had any before–after component). These factors strictly limit the inferences that can be drawn from such studies. A broadening of the current knowledge base in terms of both species and geography, as well as more robust study design, is needed to assess the impacts to wildlife.

BEST MANAGEMENT PRACTICES AND ON-SITE MITIGATION

Identifying the wide variety of energy development-driven impacts to wildlife is the first step in understanding how each sector is altering environments. Subsequently, providing tangible recommendations on mitigating these impacts is important to successful conservation actions aimed at ensuring more sustainable development. Here, we summarise the BMPs and on-site mitigation measures suggested in the published literature and highlight the need for such research where it is lacking (see also Appendix S1).

Wind

Direct mortality, the primary impact to wildlife from wind energy development, is more easily quantified than the often indirect impacts related to other sectors. Thus, in many cases, mitigation can produce more tangible results (i.e. mortality reduction), and a number of studies directly assessed mitigation in a before–after context (Fig. 3). For bats, increasing the wind speed at which turbines begin spinning (cut-in speed) was shown to effectively reduce mortalities (Baerwald *et al.* 2009; Arnett *et al.* 2010). For birds, seasonal stoppages, upgrading turbines to newer and taller models, moving food sources to reduce collision potential and stopping turbines during certain wind conditions reduced mortalities (Smallwood & Karas 2009; Smallwood *et al.* 2009; Martinez-Abrain *et al.* 2012). In addition, in areas of intensive monitoring, stopping specific turbines when birds were seen flying nearby reduced mortalities (de Lucas *et al.* 2012).

The above studies provided the best guidance on mitigation measures. Despite the fact that many studies were not designed to directly test mitigation (Fig. 3), documentation of disproportionate mortality at certain turbines or wind farms was used to suggest BMPs and on-site mitigation measures. Chief among these measures was locating wind farms to avoid areas of generally high density of birds and bats, feeding and foraging sites for soaring birds, migratory routes, nesting areas and bat colonies (Kuvlesky *et al.* 2007; Smallwood *et al.* 2007; Carrete *et al.* 2009; Baerwald & Barclay 2011; Dahl *et al.* 2012). Risks associated with development siting can be readily assessed in the pre-development environmental impact assessment stage; however, in some cases, such assessments were misleading (e.g. Ferrer *et al.* 2012) and would be more accurate if conducted at the individual turbine level taking species-specific factors into account (e.g. for soaring birds avoid placement in areas that produce certain winds; de Lucas *et al.* 2008; de Lucas *et al.* 2012; Ferrer *et al.* 2012). For bats, echolocation detectors were suggested to be effective for such assessments (Weller & Baldwin 2012). In addition, building wind farms on developed lands (e.g. agricultural lands) could benefit wildlife by reducing land-use change (Kiesecker *et al.* 2011). Aside from adequately assessing the locations of wind farms, stopping wind turbines during times when bats and birds are particularly active or vulnerable (for birds during times when food was limited; Martinez-Abrain *et al.* 2012; for bats when insects were most active, during clearer weather, falling barometric pressure, just after sunset and particularly at taller turbines; Barclay *et al.* 2007; Horn *et al.* 2008; Baerwald & Barclay 2011) was projected to provide the greatest reduction in mortalities. In addition, assessing the effectiveness of seasonal shutdowns is recommended (Johnson *et al.* 2004), as is removal of specific turbines at which there are a disproportionate number of collisions (Carrete *et al.* 2009). Habitat offsets, particularly for areas with traits described

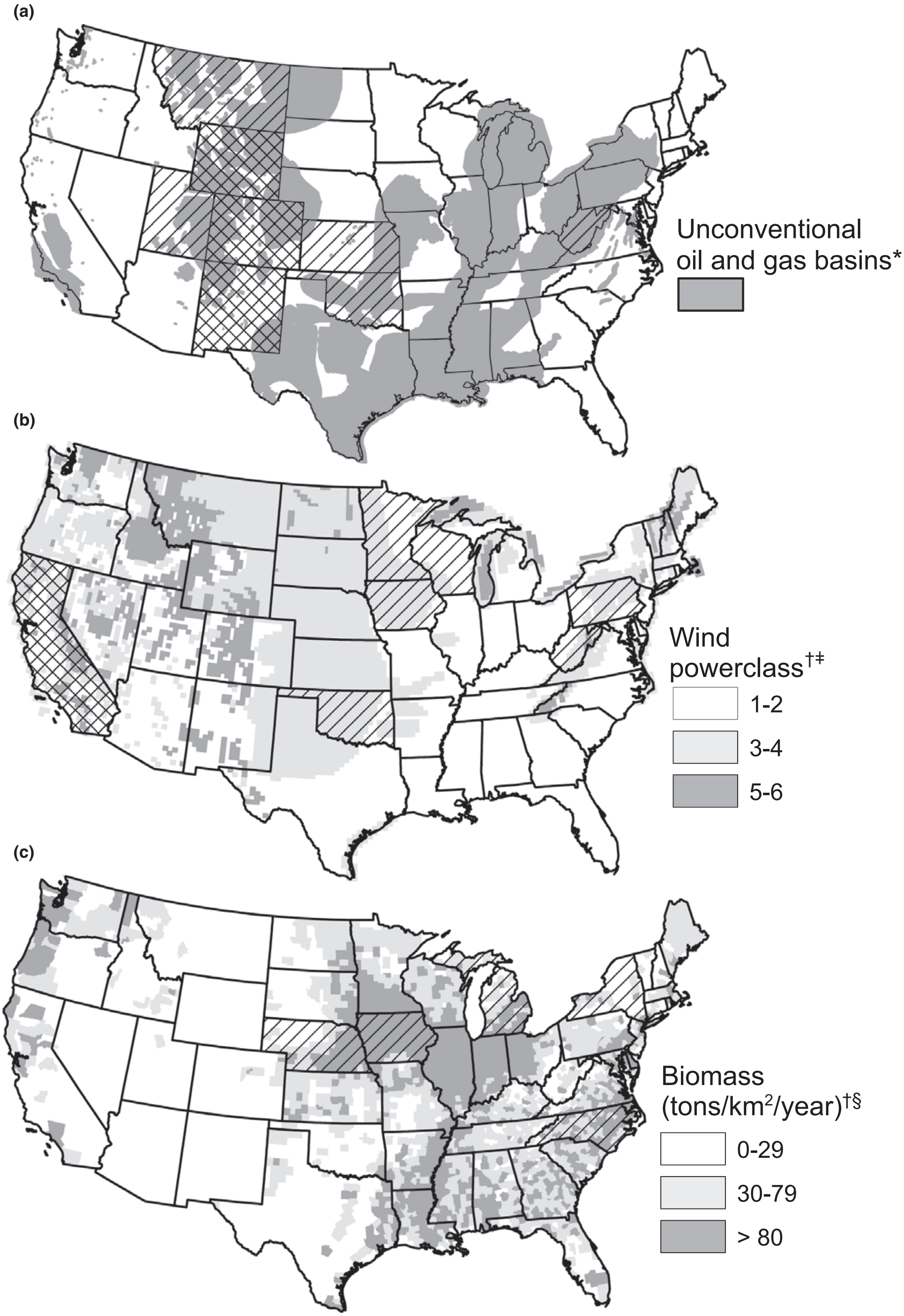

Figure 2 Location of reviewed studies and energy potential by sector in the US for (a) unconventional oil and natural gas, (b) wind energy and (c) bioenergy. Diagonal lines indicate states where 1–5 studies have been conducted, and cross-hatches indicate states where greater than 5 studies have been conducted. *Unconventional oil and natural gas basin layers obtained from the US Energy Information Administration (http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm). †Wind and biomass layers obtained from the National Renewable Energy Laboratory (http://www.nrel.gov/gis/). ‡Power classes indicate the wind energy potential estimated from 50-m wind speeds, with 1 being the lowest and 6 the highest. §Values for biomass represent potential tons/km^2/year of both biofuels and biomass burned for heating and electricity.

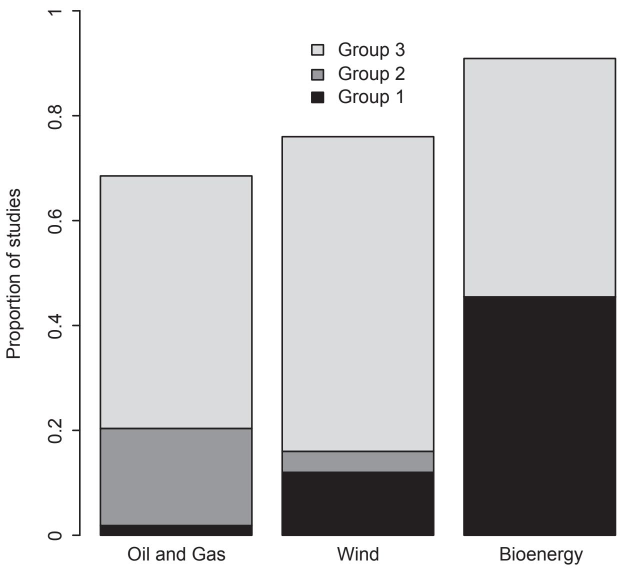

Figure 3 Proportion of US- and Canada-focused studies that discuss mitigation, categorised by study design; (1) studies that explicitly assessed the response of wildlife to the implementation or simulation of a BMP or mitigation measure, with a before–after component (for bioenergy this includes studies examining harvest practices and different plant cultivars), (2) correlative studies that were designed to directly assess the response of wildlife to existing mitigation, and (3) correlative studies that examined the response of wildlife to development and inferred mitigation from their findings.

above, have been suggested as a means of decreasing population-level impacts to birds (Smallwood & Thelander 2008). Other mitigation measures, such as altering the physical characteristics of turbines, may be effective but vary geographically, and among species in the same area (see Appendix S1). Many of these recommendations likely are species and site specific and not widely applicable.

While most of the research on wind energy impacts to wildlife focused on mortalities among avian and bat species, research on non-volant species was limited and produced equivocal results (see Appendix S1). Impacts are likely species and site specific and will require further research to elucidate general patterns useful for mitigation.

Bioenergy

Suggested measures for the mitigation of bioenergy impacts to wildlife varied widely depending on the crop and region. In tropical regions, where crops often replaced native forests, extensive pre-development assessments of economic benefits and environmental costs were suggested to fully understand impacts (Danielsen *et al.* 2009). In addition, if crops replace areas of high conservation value, habitat offsets may be required to ensure sufficient habitat is left unaltered (Edwards *et al.* 2010). In some cases, improvements within plantations (e.g. promoting understory or epiphytic growth) and maintenance of forest fragments nearby plantations were suggested to enhance biodiversity (Koh 2008). Ultimately, ensuring large tracts of native forest are left intact will provide the greatest conservation benefit.

In temperate regions, the cultivation of bioenergy crops may require no new development (i.e. use of previously cultivated lands). In these areas, degraded land brought back into production with high-diversity polycultures of plants could in fact increase habitat for some wildlife species (Tilman *et al.* 2006). Thus, the discussion of BMPs and mitigation in temperate regions centred not on the development itself but on the conservation value of the cultivated land and what crops were planted. A greater proportion of studies directly assessed mitigation for this sector than any other (Fig. 3), and a number of suggestions for BMPs and mitigation were provided. For birds that may nest in bioenergy crops, harvesting post-fledging was offered as an important BMP (Roth *et al.* 2005). In addition, maintaining habitat structure through planting mosaics of harvested and unharvested crops, or crops and undisturbed land, was suggested to provide a greater amount of habitat for a range of species (Murray & Best 2003; Roth *et al.* 2005; Sage *et al.* 2010). With short-rotation woody crops, the specific vegetative characteristics of cultivated species influenced nesting propensity for certain species of birds, and therefore, site and species-specific guidelines will need to be developed in new areas (Verschuyl *et al.* 2011). As with herbaceous crops, in short-rotation woody crops, maintaining habitat diversity by planting a variety of cultivars positively impacted a diverse array of species (Dhondt *et al.* 2007). For small mammals, habitat appeared to be enhanced by maintaining residual coarse woody debris and constructing piles or windrows (Sullivan *et al.* 2011; Appendix S1). We caution that the literature on bioenergy was limited in geographical extent and with expansion of these crops into other countries, mitigation measures will depend greatly on current land-use and management goals (e.g. if endangered species are present in an area, then general species diversity likely will be of lesser concern).

A number of other studies assessed wildlife response to bioenergy crops and made mitigation suggestions based on their findings. High-diversity polycultures (Tilman *et al.* 2006) or crops that mimic native vegetation were recommended for planting on degraded lands (Semere & Slater 2007; Meehan *et al.* 2010; Robertson *et al.* 2011a,b). Again, any measures that increase habitat diversity or maintain within-crop structural variability, such as rotational harvest or planting crops at the intersection of two habitat types, are likely to increase habitat for a range of species (Berg 2002; Sage *et al.* 2006; Robertson *et al.* 2011a). Finally, maintaining weed species within crops through soil disturbance during harvest or maintaining crops in different stages of maturity was offered as a means to provide food sources and habitat for wildlife species (Bellamy *et al.* 2009; Fry & Slater 2011). In contrast, cultivation of crop margins, lands in conservation holdings and the conversion of native habitats negatively impacted wildlife (Riffell *et al.* 2011).

Unconventional oil and gas

Unconventional oil and natural gas differs from other sectors in that, typically, the energy resource, and thus the extraction period, is finite (although we note that new technologies can extend the life span of infrastructure, with development potentially lasting several decades). Therefore, on-site mitigation and BMPs are critical for bringing wildlife through the development period, after which habitat can be restored. Several BMPs and on-site mitigation measures were outlined to address the impacts of this sector (Table 2). However, few studies were designed to directly test mitigation in a before–after comparison, or even correlatively (Fig. 3), and thus, few measures were supported in the literature. Those studies that were designed in this manner provided the most definitive evidence for the efficacy of specific BMPs or on-site mitigation and we first discuss these measures.

While unconventional oil and natural gas development typically only removes a small proportion of physical habitat (oil sands mining being a notable exception), the location and interface of these surface disturbances with wildlife space use can amplify or reduce its impacts. Several methods were suggested to manage this interface. Anthropogenic noise that elicits a multitude of behavioural responses by wildlife, our understanding of which is in its infancy, can be managed with a number of methods. Such methods included selective placement in relation to natural noise barriers, installing fewer, centralised compressors, constructing noise retaining walls, or installing noise suppression devices on compressors (Bayne *et al.* 2008; Francis *et al.* 2011; Appendix S1). Similarly, installation of remote liquid gathering systems reduced human activity at well pads and thus decreased behavioural impacts (Sawyer *et al.* 2009a). Clustering developments, maintaining buffers between development and critical habitat (e.g. nesting habitat) and designing projects to maintain sufficient cover or 'refuge' habitat were recommended to provide haven from the perceived risk associated with development (Sawyer *et al.* 2009a; Appendix S1). Particularly, if developments are clustered in future projects, maintenance of sufficient undeveloped habitat will be important to avoid numerous large development clusters with little habitat in between. Reducing the fragmentation caused by linear features (i.e. pipelines and seismic lines) so as to limit impediment to wildlife movement or territory formation was suggested by revegetation or simply constructing more narrow features, particularly in areas of extensive seismic exploration (e.g. boreal Canada; Machtans 2006). Finally, issues associated with birds landing on wastewater ponds were reduced by using innovative deterrent methods or by placing netting over ponds (Ronconi & Cassady St. Clair 2006; Ramirez 2010).

Although the above studies provided the best guidance for mitigation, a number of other studies made useful suggestions based on documentation of wildlife response to development. Such suggestions, while less supported than those above, provide useful starting points for more directed studies of mitigation measures. Specifically, employing methods to decrease infrastructure and human activity were commonly suggested mitigation measures from studies documenting behavioural responses to development. Limiting public access to industrial roads also was recommended to decrease mortalities of some mammal species (Nielsen *et al.* 2006; Dzialak *et al.* 2011). Helicopter-assisted or remote seismic exploration could decrease behavioural impacts and subsequent displacement of and stress to some wildlife species in the long term, although care must be taken as the use of helicopters negatively impacts other species (Dyer *et al.* 2002; Doherty *et al.* 2010; Kolowski & Alonso 2010; Wasser *et al.* 2011). Helicopter-assisted exploration may be particularly important in tropical areas, where fragmentation leads to progressively greater threats to biodiversity (Laurance *et al.* 2009). The above measures will provide disproportionate benefits for certain species (e.g. African elephants: *Loxodonta africana*; Rabanal *et al.* 2010), or if employed during sensitive time periods (e.g. lekking for sage grouse) or in sensitive habitat (e.g. nesting habitat; Lyon & Anderson 2003). In instances where the buffering of critical habitat or maintenance of refuge habitat is not possible, enhancing existing habitat through treatments or planting of native vegetation may be effective alternatives (Aldridge & Boyce 2007). Habitat improvements also could be used to offset nutritional stress that may occur with development disturbance. Finally, in areas where bushmeat hunting is of particular concern, resource extraction companies may need to prohibit human access and hunting (Thibault & Blaney 2003).

On-site mitigation and BMPs have the potential to effectively reduce impacts of unconventional oil and natural gas development on certain species. Other species, however, simply do not coexist well with energy development. Numerous studies documented negative impacts to both caribou and greater sage grouse from development in the US and Canada, and while BMPs and on-site mitigation measures were suggested by some studies, these typically involved maintaining large tracts of undeveloped land or employing large buffer distances between development and critical habitat (see Appendix S1). Such measures may only be viable in limited circumstances and, in the best case, will be difficult to implement; identifying critical habitat (buffered adequately from development) and determining how much is required are daunting tasks and likely to be inexact. Thus, for these species, prioritising habitat or populations to keep undeveloped, while promoting development in other areas (i.e. habitat offsets), may be the most effective mitigation measures (Doherty *et al.* 2010; Schneider *et al.* 2010). For better or worse, such measures can only be undertaken after sufficient evidence has been accrued to indicate the lack of effective BMPs or on-site mitigation measures.

Solar and geothermal

We found no research on mitigating the impacts of solar or geothermal development on wildlife; thus, no recommendations were supported by the literature. Energy is produced from these sectors in most regions of the world (Table 1), and the most likely impacts from both sectors are displacement from areas around development, leading to altered species composition and behaviour (Table 2). Best management practices and mitigation measures from other sectors are likely to be applicable; in particular, proper siting of these developments through pre-development assessments will undoubtedly be of importance in reducing impacts to wildlife.

MITIGATION FOR A SUSTAINABLE ENERGY FUTURE

Recent and emerging energy development impacts wildlife species through the reduction and fragmentation of habitat, displacement, and direct mortality, all of which can contribute to population declines. At the same time, energy development provides numerous societal benefits and is a strategically important domestic objective for many countries. Thus, reduction of impacts through creative mitigation measures and BMPs will be important for resolving these contradictory issues and securing a sustainable energy future.

While the development of mitigation measures and BMPs is in its infancy in many areas and sectors, the literature offered a number of promising measures. Common to all reviewed energy sectors was the importance of rigorous pre-development assessments. Determining environmental characteristics of areas slated for development and dynamics in wildlife occupancy is essential for predicting likely impacts. In many cases, such assessments will lead to the identification of sites where mitigation may be economically unfeasible (e.g. migratory flyways requiring shutting down of wind farms for large portions of the year). In these cases, areas of higher conservation priority may be unsuitable for the proposed energy development and could be protected as an offset for development of less important areas (Doherty *et al.* 2010; Schneider *et al.* 2010).

In regions where development is deemed to be feasible, assessments can provide further guidance on which BMPs or mitigation measures will be most effective. In general, the literature suggested that impacts of all of the reviewed sectors can be reduced by spatially and temporally consolidating development activity and infrastructure, thereby localising impacts. Any methods that reduce human activity and presence on the land (e.g. liquid gathering systems at natural gas well pads) or decrease the propagation of anthropogenic noise (e.g. concentrated compressor stations with sound retaining barriers) appear to be broadly applicable as well. Unfortunately, the mitigation approaches suggested in the literature tended to be less targeted and our understanding of their effectiveness is limited. In particular, with oil and natural gas development, there are multiple interacting, and potentially synergistic impacts (e.g. sound disturbance, fragmentation, human activity), and few studies pinpointed the mechanisms eliciting wildlife responses. In contrast, due to the nature of development and of impacts, assessments of mitigation for wind and bioenergy tended to be more straightforward, and the literature provided suggestions for mitigation in greater detail. Despite the broad generalities discussed here, measures reported may be valid only at the development densities and for the particular disturbances studied. It is likely that development thresholds exist, and exceeding these thresholds will lead to population-level consequences. Few studies addressed such prospects, but it is important that potential thresholds are investigated. In addition, due to the lack of research in many ecoregions and countries that are or will become developed (Fig. 2; Tables 1 and 3), the applicability of the BMPs and mitigation measures outlined above to other areas is uncertain.

While pre-development assessments are clearly desirable for any development project, we note that energy infrastructure currently exists for which assessments can no longer be made. In such cases, several of the above mitigation measures may not be possible (e.g. selecting infrastructure location), and measures that can be implemented retroactively should be attempted, while other measures not dependent on pre-development assessments (e.g. increasing wind turbine cut-in speed) should be explored.

Despite the mitigation measures offered above, a preponderance of the reviewed studies was not designed to explicitly test mitigation (Fig. 3). Indeed, in the literature from the US and Canada, 36% of oil and gas studies, 30% of wind studies and 23% of bioenergy studies made no mention of measures to mitigate documented impacts. Only 19% of oil and gas studies, 15% of wind studies and 38% of bioenergy studies were designed to examine the effectiveness of mitigation in a before–after context or even correlatively (Groups 1 and 2 in Fig. 3; Appendix S2). Furthermore, we note that for many studies it was often difficult to determine the extent to which the effectiveness of mitigation measures was assessed. Thus, the majority of suggested BMPs and mitigation measures discussed above should be considered provisional, until they are examined by future studies, in different ecological contexts, and with robust study designs aimed at directly assessing mitigation. In addition, a handful of studies were designed to allow for assessments of mitigation, but did not report on this aspect. We urge researchers to put BMPs and mitigation at the forefront of their findings, as this will aid future researchers, managers, regulators and industry.

The above shortcomings have led to a situation where the current literature is not broad enough to provide mitigation strategies for the breadth of species and ecosystems being affected by expansion of unconventional and renewable energy development. Furthermore, the paucity of research on the impacts to ecoregions, sectors, species and entire countries is a concern as we move forward with best practices and mitigation recommendations. Importantly, we found limited research on the impacts of development to amphibians and reptiles. In the US and Canada, little work was published from the eastern US, where large-scale natural gas development has been ongoing in the Marcellus shale, and where entire ecoregions lie squarely within some of the richest reserves on the continent (Table 3; Appendix S2). Globally, the lack of research from entire countries and regions is even more apparent (Table 1).

Addressing the shortcomings in the energy development literature will require a shift from solely identifying impacts to directly addressing BMPs and on-site mitigation measures that can be part of sustainable solutions to development impacts. Such a direction will require studies that either seek to obtain a mechanistic understanding of development impacts (i.e. what is actually causing documented patterns) or directly test BMPs and mitigation measures in an experimental framework. Such efforts will require collaboration with both industry and government regulatory agencies and will hold numerous benefits for all involved. Knowledge of development plans can be used to implement before-after-control-impact designs, dialogue with industry and regulatory agencies can allow for studies that directly assess the efficacy of economically and biologically feasible mitigation measures and BMPs (see Arnett *et al.* 2010 for an example), and finally, collaborations increase the likelihood of actual implementation of research findings. These collaborations will require researchers willing to engage industry, but also it is essential that industry is open and transparent with development data and plans, as such information is a necessity for robust study designs. Furthermore, it is crucial that industry abides by development plans where such plans formed the basis for research design, as alteration of development activities can be fatal to research projects and, therefore, our ability to derive meaningful inference about the system and question. Ideally, collaborative planning needs to be implemented in the pre-development process to ensure the greatest return from such endeavours. We note that such a shift will take time to implement, and as noted above, energy development already has occurred in vast areas throughout the world. Thus, mitigation measures that show the most promise should be implemented immediately, but their provisional nature must be understood by all involved. These measures can be assessed for their efficacy regularly and an adaptive framework can be used to alter mitigation when necessary.

Due to the known environmental impacts of energy development, funds will continue to be available for mitigation and BMPs. Applied wildlife ecology research must play a role in reconciling the intertwined costs and benefits of development and provide realistic recommendations for the most effective use of such funds. We call for researchers to unambiguously outline the BMPs and on-site mitigation measures suggested by their results, and to be more explicit in the recommendation of potentially subjective measures, such as habitat offsets and maintenance of critical habitat (i.e. how much, what type and what entails critical habitat). Such efforts will ensure a greater probability of implementation of BMPs and on-site mitigation measures, and a more efficient and effective use of funds. Large-scale domestic energy development represents a new reality for terrestrial ecosystems, and conservation consequences are inevitable. Designing and implementing creative and effective BMPs and on-site mitigation measures will be one of the major conservation challenges of the next 20 years. Current research must rise to meet this reality with innovative studies designed to address these challenges.

ACKNOWLEDGEMENTS

We thank C.R. Anderson Jr. for stimulating conversations on energy development and wildlife and for reviewing an earlier version of the manuscript. We thank ExxonMobil Corporation and Colorado Parks and Wildlife for stimulating this research through support of research on the impact of energy development in the Piceance Basin, CO. We thank A.B.A. Shafer, the editor and 3 anonymous reviewers for helpful comments that greatly improved the manuscript.

STATEMENT OF AUTHORSHIP

JMN and GW conceived and designed the study. JMN conducted the literature search and summarised results. JMN conducted data analysis. JMN and GW wrote the manuscript.

REFERENCES

Aldridge, C.L. & Boyce, M.S. (2007). Linking occurrence and fitness to persistence: Habitat-based approach for endangered Greater Sage-Grouse. *Ecol. Appl.*, 17, 508–526.

Arnett, E.B., Huso, M.M.P., Schirmacher, M.R. & Hayes, J.P. (2010). Altering turbine speed reduces bat mortality at wind-energy facilities. *Front. Ecol. Environ.*, 9, 209–214.

Baerwald, E.F. & Barclay, R.M.R. (2011). Patterns of activity and fatality of migratory bats at a wind energy facility in Alberta Canada. *J. Wildl. Manage.*, 75, 1103–1114.

Baerwald, E.F., Edworthy, J., Holder, M. & Barclay, R.M.R. (2009). A large-scale mitigation experiment to reduce bat fatalities at wind energy facilities. *J. Wildl. Manage.*, 73, 1077–1081.

Barclay, R.M.R., Baerwald, E.F. & Gruver, J.C. (2007). Variation in bat and bird fatalities at wind energy facilities: assessing the effects of rotor size and tower height. *Can. J. Zool.*, 85, 381–387.

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. *Conserv. Biol.*, 22, 1186–1193.

Bellamy, P.E., Croxton, P.J., Heard, M.S., Hinsley, S.A., Hulmes, L., Hulmes, S. *et al.* (2009). The impact of growing miscanthus for biomass on farmland bird populations. *Biomass Bioenergy*, 33, 191–199.

Berg, A. (2002). Breeding birds in short-rotation coppices on farmland in central Sweden - the importance of Salix height and adjacent habitats. *Agric. Ecosyst. Environ.*, 90, 265–276.

Buddenhagen, C.E., Chimera, C. & Clifford, P. (2009). Assessing biofuel crop invasiveness: a case study. *PLoS ONE*, 4, e5261.

Bui, T.V.D., Marzluff, J.M. & Bedrosian, B. (2010). Common raven activity in relation to land use in western wyoming: implications for greater sage-grouse reproductive success. *Condor*, 112, 65–78.

Butler, R.A. & Laurance, W.G. (2009). Is oil palm the next emerging threat to the Amazon? *Tropical Conservation Science*, 2, 1–10.

Carrete, M., Sánchez-Zapata, J.A., Benítez, J.R., Lobón, M. & Donázar, J.A. (2009). Large scale risk-assessment of wind-farms on population viability of a globally endangered long-lived raptor. *Biol. Conserv.*, 142, 2954–2961.

Dahl, E.L., Bevanger, K., Nygard, T., Roskaft, E. & Stokke, B.G. (2012). Reduced breeding success in white-tailed eagles at Smola windfarm, western Norway, is caused by mortality and displacement. *Biol. Conserv.*, 145, 79–85.

Danielsen, F., Beukema, H., Burgess, N.D., Parish, F., BrÜHl, C.A., Donald, P. F. *et al.* (2009). Biofuel plantations on forested lands: double jeopardy for biodiversity and climate. *Conserv. Biol.*, 23, 348–358.

Dhondt, A.A., Wrege, P.H., Cerretani, J. & Sydenstricker, K.V. (2007). Avian species richness and reproduction in shortrotation coppice habitats in central and western New York. *Bird Study*, 54, 12–22.

Dinçer, F. (2011). The analysis on photovoltaic electricity generation status, potential and policies of the leading countries in solar energy. *Renew. Sust. Energ. Rev.*, 15, 713–720.

Doherty, K.E., Naugle, D.E., Walker, B.L. & Graham, J.M. (2008). Greater sage-grouse winter habitat selection and energy development. *J. Wildl. Manage.*, 72, 187–195.

Doherty, K.E., Naugle, D.E. & Evans, J.S.. (2010). A Currency for offsetting energy development impacts: horse-trading sage-grouse on the open market. *PLoS ONE*, 5, e10339.

Dyer, S.J., O'Neill, J.P., Wasel, S.M. & Boutin, S. (2002). Quantifying barrier effects of roads and seismic lines on movements of female woodland caribou in northeastern Alberta. *Can. J. Zool.*, 80, 839–845.

Dzialak, M.R., Webb, S.L., Harju, S.M., Winstead, J.B., Wondzell, J.J., Mudd, J.P. *et al.* (2011). The spatial pattern of demographic performance as a component of sustainable landscape management and planning. *Landscape Ecol.*, 26, 775–790.

Edwards, D.P., Hodgson, J.A., Hamer, K.C., Mitchell, S.L., Ahmad, A.H., Cornell, S.J. *et al.* (2010). Wildlife-friendly oil palm plantations fail to protect biodiversity effectively. *Conserv. Lett.*, 3, 236–242.

Erturk, M. (2011). Economic analysis of unconventional liquid fuel sources. *Renew. Sust. Energ. Rev.*, 15, 2766–2771.

European Commission (2009). *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.* Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF. Last accessed June 15, 2012.

Fargione, J.E., Plevin, R.J. & Hill, J.D. (2010). The ecological impact of biofuels. *Ann. Rev. Ecol. Evol. Syst.*, 41, 351–377.

Ferrer, M., de Lucas, M., Janss, G.F.E., Casado, E., Muñoz, A.R., Bechard, M.J. *et al.* (2012). Weak relationship between risk assessment studies and recorded mortality in wind farms. *J. Appl. Ecol.*, 49, 38–46.

Fitzherbert, E.B., Struebig, M.J., Morel, A., Danielsen, F., Brühl, C.A., Donald, P.F. *et al.* (2008). How will oil palm expansion affect biodiversity?. *Trends Ecol. Evol.*, 23, 538–545.

Francis, C.D., Ortega, C.P. & Cruz, A.. (2011). Different behavioural responses to anthropogenic noise by two closely related passerine birds. *Biol. Lett.*, 7, 850–852.

Francis, C.D., Kleist, N.J., Ortega, C.P. & Cruz, A.. (2012). Noise pollution alters ecological services: enhanced pollination and disrupted seed dispersal. *Proc. R. Soc. B: Biol.*, 279, 2727–2735.

Fry, D.A. & Slater, F.M. (2011). Early rotation short rotation willow coppice as a winter food resource for birds. *Biomass. Bioenerg.*, 35, 2545–2553.

Garvin, J.C., Jennelle, C.S., Drake, D. & Grodsky, S.M. (2011). Response of raptors to a windfarm. *J. Appl. Ecol.*, 48, 199–209.

Gilbert, M.M. & Chalfoun, A.D. (2011). Energy development affects populations of sagebrush songbirds in wyoming. *J. Wildl. Manage.*, 75, 816–824.

Gurney, K.E., Williams, T.D., Smits, J.E., Wayland, M., Trudeau, S. & Bendell-Young, L.I. (2005). Impact of oil-sands based wetlands on the growth of mallard (Anas platyrhynchos) ducklings. *Environ. Toxicol. Chem.*, 24, 457–463.

Holloran, M.J., Kaiser, R.C. & Hubert, W.A. (2010). Yearling greater sage-grouse response to energy development in wyoming. *J. Wildl. Manage.*, 74, 65–72.

Horn, J.W., Arnett, E.B. & Kunz, T.H. (2008). Behavioral responses of bats to operating wind turbines. *J. Wildl. Manage.*, 72, 123–132.

Intergovernmental Panel on Climate Change (2007). *Climate Change 2006: Synthesis Report.* Available at: http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm. Last accessed September 30, 2011.

International Energy Agency (2009). *World Energy Outlook 2009.* Available at: http://www.iea.org/W/bookshop/add.aspx?id = 388. Last accessed October 30, 2011.

Jarnevich, C.S. & Laubhan, M.K. (2011). Balancing energy development and conservation: a method utilizing species distribution models. *Environ. Manage.*, 47, 926–936.

Johnson, G.D., Perlik, M.K., Erickson, W.P. & Strickland, M.D. (2004). Bat activity, composition, and collision mortality at a large wind plant in Minnesota. *Wildlife Soc. B.*, 32, 1278–1288.

Kerr, R.A. (2010). Natural gas from shale bursts onto the scene. *Science*, 328, 1624–1626.

Kerr, R.A. (2011). Peak oil production may already be here. *Science*, 331, 1510–1511.

Kiesecker, J.M., Evans, J.S., Fargione, J., Doherty, K., Foresman, K.R., Kunz, T. H. *et al.* (2011). Win-win for wind and wildlife: a vision to facilitate sustainable development. *PLoS ONE*, 6, e17566.

Koh, L.P. (2008). Can oil palm plantations be made more hospitable for forest butterflies and birds? *J. Appl. Ecol.*, 45, 1002–1009.

Koh, L.P., Miettinen, J., Liew, S.C. & Ghazoul, J. (2011). Remotely sensed evidence of tropical peatland conversion to oil palm. *Proc. Natl. Acad. Sci. USA*, 108, 5127–5132.

Kolowski, J.M. & Alonso, A. (2010). Density and activity patterns of ocelots (Leopardus pardalis) in northern Peru and the impact of oil exploration activities. *Biol. Conserv.*, 143, 917–925.

Kunz, T.H., Arnett, E.B., Erickson, W.P., Hoar, A.R., Johnson, G.D., Larkin, R.P. *et al.* (2007). Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. *Front. Ecol. Environ.*, 5, 315–324.

Kuvlesky, W.P., Brennan, L.A., Morrison, M.L., Boydston, K.K., Ballard, B.M. & Bryant, F.C. (2007). Wind energy development and wildlife conservation: challenges and opportunities. *J. Wildl. Manage.*, 71, 2487–2498.

Laurance, W.F. (2007). Switch to corn promotes amazon deforestation. *Science*, 318, 1721.

Laurance, W.F., Goosem, M. & Laurance, S.G.W. (2009). Impacts of roads and linear clearings on tropical forests. *Trends Ecol. Evol.*, 24, 659–669.

Leu, M., Hanser, S.E. & Knick, S.T. (2008). The human footprint in the west: a large-scale analysis of anthropogenic impacts. *Ecol. Appl.*, 18, 1119–1139.

Lovich, J.E. & Ennen, J.R. (2011). Wildlife conservation and solar energy development in the desert southwest, united states. *Bioscience*, 61, 982–992.

Lu, X., McElroy, M.B. & Kiviluoma, J. (2009). Global potential for wind-generated electricity. *P. Natl. Acad. Sci. USA*, 106, 10933–10938.

de Lucas, M., Janss, G.F.E. & Ferrer, M. (2004). The effects of a wind farm on birds in a migration point: the Strait of Gibraltar. *Biodivers. Conserv.*, 13, 395–407.

de Lucas, M., Janss, G.F.E., Whitfield, D.P. & Ferrer, M. (2008). Collision fatality of raptors in wind farms does not depend on raptor abundance. *J. Appl. Ecol.*, 45, 1695–1703.

de Lucas, M., Ferrer, M., Bechard, M.J. & Muñoz, A.R. (2012). Griffon vulture mortality at wind farms in southern Spain: distribution of fatalities and active mitigation measures. *Biol. Conserv.*, 147, 184–189.

Lyon, A.G. & Anderson, S.H. (2003). Potential gas development impacts on sage grouse nest initiation and movement. *Wildlife Soc. B.*, 31, 486–491.

Machtans, C.S. (2006). Songbird response to seismic lines in the western boreal forest: a manipulative experiment. *Can. J. Zool.*, 84, 1421–1430.

Martinez-Abrain, A., Tavecchia, G., Regan, H.M., Jimenez, J., Surroca, M. & Oro, D. (2012). Effects of wind farms and food scarcity on a large scavenging bird species following an epidemic of bovine spongiform encephalopathy. *J. Appl. Ecol.*, 49, 109–117.

McDonald, R.I., Fargione, J., Kiesecker, J., Miller, W.M. & Powell, J.. (2009). Energy sprawl or energy efficiency: climate policy impacts on natural habitat for the united states of america. *PLoS ONE*, 4, e6802.

Meehan, T.D., Hurlbert, A.H. & Gratton, C. (2010). Bird communities in future bioenergy landscapes of the Upper Midwest. *P. Natl. Acad. Sci. USA*, 107, 18533–18538.

Murray, L.D. & Best, L.B. (2003). Short-term bird response to harvesting switchgrass for biomass in iowa. *J. Wildl. Manage.*, 67, 611–621.

Nepstad, D.C., Stickler, C.M., Soares, B. & Merry, F. (2008). Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philos. T. R. Soc. B.*, 363, 1737–1746.

Nielsen, S.E., Stenhouse, G.B. & Boyce, M.S. (2006). A habitat-based framework for grizzly bear conservation in Alberta. *Biol. Conserv.*, 130, 217–229.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V. N., Underwood, E.C. *et al.* (2001). Terrestrial ecoregions of the world: a new map of life on earth. *Bioscience*, 51, 933–938.

Pearce-Higgins, J.W., Stephen, L., Langston, R.H.W., Bainbridge, I.P. & Bullman, R. (2009). The distribution of breeding birds around upland wind farms. *J. Appl. Ecol.*, 46, 1323–1331.

Pimental, D. (2008). Renewable and solar energy technologies: energy and environmental issues. In *Biofuels, Solar and Wind as Renewable Energy Systems* (ed. Pimental, D.). Springer Science, Ithaca, NY, pp. 1–18.

Pitman, J.C., Hagen, C.A., Robel, R.J., Loughin, T.M. & Applegate, R.D. (2005). Location and success of lesser prairie-chicken nests in relation to vegetation and human disturbance. *J. Wildl. Manage.*, 69, 1259–1269.

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. *Biol. Conserv.*, 143, 1017–1024.

Ramirez, P. (2010). Bird mortality in oil field wastewater disposal facilities. *Environ. Manage.*, 46, 820–826.

Riffell, S.A.M., Verschuyl, J., Miller, D. & Wigley, T.B. (2011). A meta-analysis of bird and mammal response to short-rotation woody crops. *GCB Bioenergy*, 3, 313–321.

Robertson, B.A., Doran, P.J., Loomis, E.R., Robertson, J.R. & Schemske, D.W. (2011a). Avian use of perennial biomass feedstocks as post-breeding and migratory stopover habitat. *PLoS ONE*, 6, e16941.

Robertson, B.A., Doran, P.J., Loomis, L.R., Robertson, J.R. & Schemske, D.W. (2011b). Perennial biomass feedstocks enhance avian diversity. *GCB Bioenergy*, 3, 235–246.

Ronconi, R.A. & Cassady St. Clair, C. (2006). Efficacy of a radar-activated on-demand system for deterring waterfowl from oil sands tailings ponds. *J. Appl. Ecol.*, 43, 111–119.

Roth, A.M., Sample, D.W., Ribic, C.A., Paine, L., Undersander, D.J. & Bartelt, G.A. (2005). Grassland bird response to harvesting switchgrass as a biomass energy crop. *Biomass. Bioenerg.*, 28, 490–498.

Rydell, J., Bach, L., Dubourg-Savage, M.-J., Green, M., Rodrigues, L. & Hedenström, A. (2010). Bat mortality at wind turbines in northwestern europe. *Acta Chiropterol.*, 12, 261–274.

Sage, R., Cunningham, M. & Boatman, N. (2006). Birds in willow short-rotation coppice compared to other arable crops in central England and a review of bird census data from energy crops in the UK. *Ibis*, 148, 184–197.

Sage, R., Cunningham, M., Haughton, A.J., Mallott, M.D., Bohan, D.A., Riche, A. *et al.* (2010). The environmental impacts of biomass crops: use by birds of miscanthus in summer and winter in southwestern England. *Ibis*, 152, 487–499.

Sawyer, H., Nielson, R.M., Lindzey, F. & McDonald, L.L. (2006). Winter habitat selection of mule deer before and during development of a natural gas field. *J. Wildl. Manage.*, 70, 396–403.

Sawyer, H., Kauffman, M.J. & Nielson, R.M. (2009a). Influence of well pad activity on winter habitat selection patterns of mule deer. *J. Wildl. Manage.*, 73, 1052–1061.

Sawyer, H., Kauffman, M.J., Nielson, R.M. & Horne, J.S. (2009b). Identifying and prioritizing ungulate migration routes for landscape-level conservation. *Ecol. Appl.*, 19, 2016–2025.

Schneider, R.R., Hauer, G., Adarnowicz, W.L. & Boutin, S. (2010). Triage for conserving populations of threatened species: The case of woodland caribou in Alberta. *Biol. Conserv.*, 143, 1603–1611.

Semere, T. & Slater, F.M. (2007). Ground flora, small mammal and bird species diversity in miscanthus (*Miscanthus×giganteus*) and reed canary-grass (*Phalaris arundinacea*) fields. *Biomass Bioenergy*, 31, 20–29.

Smallwood, K.S. & Karas, B. (2009). Avian and bat fatality rates at old-generation and repowered wind turbines in california. *J. Wildl. Manage.*, 73, 1062–1071.

Smallwood, K.S. & Thelander, C. (2008). Bird mortality in the altamont pass wind resource area california. *J. Wildl. Manage.*, 72, 215–223.

Smallwood, K.S., Thelander, C.G., Morrison, M.L. & Rugge, L.M. (2007). Burrowing owl mortality in the altamont pass wind resource area. *J. Wildl. Manage.*, 71, 1513–1524.

Smallwood, K.S., Rugge, L. & Morrison, M.L. (2009). Influence of behavior on bird mortality in wind energy developments. *J. Wildl. Manage.*, 73, 1082–1098.

Sorensen, T., McLoughlin, P.D., Hervieux, D., Dzus, E., Nolan, J., Wynes, B.O. B. *et al.* (2008). Determining sustainable levels of cumulative effects for boreal caribou. *J. Wildl. Manage.*, 72, 900–905.

Stewart, G.B., Pullin, A.S. & Coles, C.F. (2007). Poor evidence-base for assessment of windfarm impacts on birds. *Environ. Conserv.*, 34, 1–11.

Sullivan, T.P., Sullivan, D.S., Lindgren, P.M.F., Ransome, D.B., Bull, J.G. & Ristea, C. (2011). Bioenergy or biodiversity? Woody debris structures and maintenance of red-backed voles on clearcuts. *Biomass Bioenergy*, 35, 4390–4398.

Thibault, M. & Blaney, S. (2003). The oil industry as an underlying factor in the bushmeat crisis in Central Africa. *Conserv. Biol.*, 17, 1807–1813.

Tilman, D., Hill, J. & Lehman, C. (2006). Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, 314, 1598–1600.

United States Energy Information Administration (2008). *Energy Independence and Security Act of 2007: Summary of Provisions*. Available at: http://www.eia.gov/oiaf/aeo/otheranalysis/aeo_2008analysispapers/eisa.html. Last accessed October 1, 2011.

United States Energy Information Administration (2010). *Annual Energy Review 2009*. Available at: http://www.eia.gov/totalenergy/data/annual/. Last accessed September 30, 2011.

Verschuyl, J., Riffell, S., Miller, D. & Wigley, T.B. (2011). Biodiversity response to intensive biomass production from forest thinning in North American forests - A meta-analysis. *Forest Ecol. Manag.*, 261, 221–232.

Walter, W.D., Vercauteren, K.C., Gilsdorf, J.M. & Hygnstrom, S.E. (2009). Crop, native vegetation, and biofuels: response of white-tailed deer to changing management priorities. *J. Wildl. Manage.*, 73, 339–344.

Wasser, S.K., Keim, J.L., Taper, M.L. & Lele, S.R. (2011). The influences of wolf predation, habitat loss, and human activity on caribou and moose in the Alberta oil sands. *Front. Ecol. Environ.*, 9, 546–551.

Weller, T.J. & Baldwin, J.A. (2012). Using echolocation monitoring to model bat occupancy and inform mitigations at wind energy facilities. *J. Wildl. Manage.*, 76, 619–631.

World Energy Council (2010). *2010 Survey of Energy Resources*. World Energy Council, London, United Kingdom, 618 pages.

World Energy Council (2012). *Survey of Energy Resources: Shale Gas - What's New*. World Energy Council, London, United Kingdom, 16 pages.

Wrege, P.H., Rowland, E.D., Thompson, B.G. & Batruch, N. (2010). Use of acoustic tools to reveal otherwise cryptic responses of forest elephants to oil exploration. *Conserv. Biol.*, 24, 1578–1585.

Zou, L., Miller, S.N. & Schmidtmann, E.T. (2006). Mosquito larval habitat mapping using remote sensing and GIS: Implications of coalbed methane development and West Nile virus. *J. Med. Entomol.*, 43, 1034–1041.

SUPPORTING INFORMATION

Additional Supporting Information may be downloaded via the online version of this article at Wiley Online Library (www.ecologyletters.com).

As a service to our authors and readers, this journal provides supporting information supplied by the authors. Such materials are peer-reviewed and may be re-organised for online delivery, but are not copy-edited or typeset. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.

Editor, Helen Regan
Manuscript received 14 May 2012
First decision made 19 June 2012
Manuscript accepted 28 August 2012