THESIS

THE IMPACT OF ENERGY SPRAWL ON BIODIVERSITY AND ECOSYSTEM SERVICES

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ABSTRACT

THE IMPACT OF ENERGY SPRAWL ON BIODIVERSITY AND ECOSYSTEM SERVICES

The future of energy production is uncertain as society demands clean and abundant energy to meet the needs of a growing and increasingly developed population. Wind energy offers the benefit of reduced greenhouse gas emissions; however, like conventional power sources such as oil and natural gas, wind energy results in an environmental footprint that contributes to energy sprawl, or the use and degradation of land due to energy production. In order to better understand these potential affects I summarized and evaluated the impacts on a diverse set of indicators including habitat loss, fragmentation, wildlife mortality, noise and light pollution, invasive species, and changes in carbon stock and water resources. I quantified these indicators by digitizing the land-use footprint within 375 randomly selected one kilometer diameter plots, stratified across each energy type, within Colorado and Wyoming, USA. I found substantial differences in impacts between energy types for most indicators, although the magnitude and direction of the differences varied. Wind energy resulted in greater impacts to noise and light pollution whereas oil and natural gas development resulted in greater habitat fragmentation and impacts to biomass carbon stock and water resources. Underlying land-use and location of production activities were a critical factor in describing the impacts. This novel technique and my specific findings can be used by developers, planners and policy-makers to design energy development that retains biodiversity while meeting society's demand for energy.

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PREFACE

The future of energy production is uncertain as society demands clean and abundant energy to meet the needs of a growing and increasingly developed population. Wind energy offers the benefit of reduced greenhouse gas emissions and is viewed as the "green" alternative to fossil fuels. As a result, the production of wind energy in the United States has grown rapidly and has seen a 15 fold increase since the year 2000. However, like conventional power sources such as oil and natural gas, wind energy results in an "environmental footprint" with repercussions for biodiversity and human well-being. Increased wind energy production, combined with a growing demand for energy from oil, natural gas and coal, is expected to cause a rapid increase in energy sprawl, or the use and degradation of land due to energy production.

The assessment of wind energy as "clean" and "green" is narrowly focused on emissions from consumption and ignores the impacts of wind energy production to the landscape. My goal was to research and test the differences between wind energy and oil and natural gas in impacts to biodiversity and ecosystem services. A better understanding of these impacts could provide policy makers, land managers and the public with the information needed for a complete and accurate understanding of the impacts of our energy alternatives. In order to assess the impacts of energy sprawl on the landscape, I selected the following set of eight unique indicators to act as surrogates for impacts to biodiversity and ecosystem services: habitat loss and fragmentation, wildlife mortality, noise and light pollution, invasive species, biomass carbon stock and water resources. In chapter one, I review the existing literature pertaining to each of these indicators. I found that empirical data on the impacts of energy sprawl is unevenly distributed among energy types, geographical regions and faunal groups. The lack of data on energy impacts on most indicators associated with biodiversity and selected ecosystem services is strongly limiting science-driven development decisions. I conclude chapter one by suggesting priorities for research and practice, including using a landscape assessment approach to predict future, cumulative impacts.

In chapter two I test the landscape assessment approach introduced in chapter one. I use the indicators listed above to quantify the impacts of oil, natural gas, and wind energy development on biodiversity and ecosystem services in Colorado and Wyoming. To quantify these impacts I digitized the land-use footprint within 375 randomly selected one kilometer diameter plots, stratified across each energy type. In order to determine how landscape characteristics influence the magnitude of impacts, each of the above indicators was modeled with a suite of covariates, including energy type, underlying land-use, land cover, land ownership, topography, elevation, housing density and median income.

I found substantial differences in impacts between energy types for most indicators, although the magnitude and direction of the differences varied. Wind energy resulted in greater impacts to noise and light pollution whereas oil and natural gas development resulted in greater habitat fragmentation, more loss of biomass carbon stock, and more water consumption. The shortage of empirical data addressed in chapter one was a significant impediment to quantifying potential wildlife mortality. Underlying land-use and location of production activities were a critical factor in describing the impacts; wind energy development tended to occur on already disturbed lands, resulting in less additional habitat loss and fragmentation compared with oil and gas development. In addition to energy type, landscape characteristics, such as housing density, land cover, and topography described a substantial portion of the variation. Impacts were also quantified per unit energy to provide a tangible connection between consumption and conservation for public awareness. Wind energy resulted in greater impacts per unit energy for

all indicators except water consumption. However, the change in some impacts over time eventually reversed this result and highlighted the difference between renewable and finite resources.

This novel technique and my specific findings can be used by developers, planners and policy-makers to design energy development that retains biodiversity while meeting society's demand for energy. My research is the first attempt to comprehensively assess the true "greenness" of wind energy development relative to conventional power sources by evaluating land use impacts on a landscape scale. The ability to quantify impacts per unit energy allows Americans to understand the conservation implications of their consumption. This knowledge may increase interest in energy policy and empower citizens to influence resource management decisions. Particularly promising is the potential of this methodology to assess land-use alternatives, cumulative impacts and long-term changes to biodiversity and ecosystem services. In particular, this framework for considering impacts could be used to understand range-wide and long-term impacts on species of concern, such as sage-grouse, for which sufficient data are available. This research method thus complements high-quality, field-based research, but acts to assess impacts to biodiversity and ecosystem services in the interim; which is important given the rapid and unprecedented extent of haphazard energy development already underway.

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CHAPTER ONE

A REVIEW OF THE IMPACTS OF ENERGY SPRAWL ON BIODIVERSITY AND ECOSYSTEM SERVICES

INTRODUCTION

Global and U.S. energy production is in the midst of a substantial transformation. Energy demand in the U.S. topped 99 quadrillion British thermal units (Btus) in 2008, with fossil fuels meeting the majority (83%) of that demand (EIA 2009). Several recent changes are driving a shift to developing more domestic renewable and fossil fuel resources, including the increasing political uncertainty in many oil-rich nations and the need to maintain energy security in the U.S. At the same time, recognition of the potential social and biological ramifications of climate change is driving the push for climate change mitigation, which in the form of renewable energy, seeks to regulate carbon emissions by exploiting carbon neutral solar and wind power (Pimentel et al. 2002). This shift towards domestic energy development is already underway: U.S. wind energy production has increased 15 fold since 2000 and U.S. natural gas production has risen by almost 28% over the last two decades (Figure 1; EIA 2009).

In comparison to oil and natural gas (and all fossil fuels), wind energy has the lowest lifecycle emissions of CO_2 and other greenhouse gases (Jacobson 2008). Many studies have indicated a significant loss in global biodiversity and ecosystem services as a result of increasing global temperatures from the use of fossil fuels (McDaniel & Borton 2002). As such, wind energy development is being promoted as a “clean” alternative to the burning of fossil fuels. However, this perspective often overlooks the impacts of energy development on the landscape, known as “energy sprawl” (McDonald et al. 2009). Like oil and natural gas, wind energy requires a network of roads, transmission lines and associated infrastructure to capture and transport the power. Information on the current and projected impacts of oil, gas and wind energy sprawl on biodiversity and ecosystem services is scarce (Figure 2) and warrants further investigation given the potential of energy development to transform natural and human-dominated landscapes (Figures 3 and 4).

Here I review and compare the impacts of oil, gas and wind energy development on various local and landscape-level indicators that may influence biodiversity and ecosystem services, including wildlife mortality, direct habitat loss, fragmentation, noise and light pollution, invasive species, and changes in carbon stocks and water resources. These indicators were chosen as surrogates for measured impacts to species diversity and the provision of many ecosystem services, which are difficult to quantify and site specific. In this review I synthesize current knowledge and highlight key areas for additional inquiry for each indicator. Lastly, I suggest a novel approach to evaluate and predict the relative impacts of energy sprawl on the landscape using existing data and spatial analysis tools.

BIODIVERSITY IMPACTS

Wildlife Mortality

Energy development can result in wildlife mortality due to collision, contamination or electrocution. Numerous reviews have synthesized data on avian and bat mortality from wind turbines (Erickson et al. 2005; Arnett et al. 2007). There are emerging concerns; however, regarding the inconsistency, poor rigor and lack of transparency of mortality studies at wind facilities worldwide (Kuvlesky et al. 2007; Piorkowski et al. 2012). The majority of data are held in consultant, agency or developer reports and are not always publicly available. For example, mortality estimates are only available for approximately 10% of all installed wind capacity in western North America (Johnson & Stephens 2011). In addition to turbines, wind facilities employ meteorological towers that are known to result in avian collision mortality (Erickson et al. 2005) and are often overlooked during mortality studies.

Wind energy facilities share other sources of mortality with oil and gas development including vehicle collisions and power line electrocution. As much as 17% of avian mortality was attributed to vehicle collisions at a Minnesota wind farm (Higgins et al. 2007). Power line electrocutions are more common amongst large birds, such as raptors, because they are capable of bridging the connection between two different phase or hot and grounded wires. Waterfowl and other birds that exhibit poor maneuverability are more likely to collide with stationary structures such as power lines (Bevanger 1998). Power line fatality rates are difficult to quantify and often underestimated (Bayne & Dale 2011), but most avian mortalities associated with power lines can be avoided through proper siting, outfitting transformers with protectants, and the use of line markers (APLIC 2006).

Sources of mortality unique to oil and gas development are contamination from waste pits and evaporation ponds used to store the byproducts of drilling. Most regulations require these pits be netted to prevent entry by wildlife, however, this does not always occur. Numerous studies have found relatively high numbers of bird carcasses in pits (Flickinger et al. 1981; Flickinger & Bunck 1987; Ramirez 2000; Ramirez 2010), such as an average of 8.4 avian fatalities per unprotected waste pit each year in Wyoming (Trail 2006). In addition, massive avian mortality events have occurred as a result of gas flare stacks at refineries (Bjorge 1987). Flare stacks and gas compressors, which emit heat, flames and toxins, are common within oil and gas fields; however, no research has investigated wildlife mortality associated with these features.

On a global scale, wind energy has the potential to exceed onshore oil and gas development in direct mortality of wildlife. Mortality from wind energy could lead to localized population level impacts and the cumulative result of wind energy production and other anthropogenic sources of mortality may cause widespread decline in avian and bat populations. All of these impacts require more consistent and rigorous monitoring. Obtaining reliable information on mortality rates under different scenarios is fundamental to identifying creative engineering and environmental solutions to minimize mortality.

Habitat Loss

Habitat loss is the leading cause of species extinction and other negative impacts to biodiversity (Pimm & Raven 2000). Although habitat loss is a species specific term, for the purposes of this review I use it to describe any direct loss of vegetation communities due to human activity. Habitat losses from energy development include well pads, turbine pads, roads, buildings, transmission lines, and surface pipelines. The surface area required by wind energy facilities and oil and natural gas development is highly variable and dependent on numerous site specific factors. Rough estimates indicate that wind energy requires 0.3 (+/- 0.3 standard deviation [SD]) hectares (ha) per megawatt (MW) or 0.50 ha (+/- 0.54 SD) per modern turbine (Denholm et al. 2009). The direct habitat loss associated with oil and natural gas development is dependent on the type of well, number of wells drilled from each pad, land ownership, topography and location. For example, future development estimates for Wyoming range from 1.5 ha per well (including pad and access roads) for shallow coal-bed methane wells to 16.4 ha for deep exploratory wells (BLM 2004). Habitat loss from roads is also substantial; accounting for the largest proportion of land-use change within oil and natural gas fields and wind facilities (Denholm et al. 2009). By 2030 wind energy is forecasted to require far more land area (72.1 ha) than oil and natural gas (44.7 and 18.6 ha, respectively) per terawatt of power produced in the U.S. (McDonald et al. 2009).

As energy needs grow, all types of energy development will expand to increasingly remote areas, requiring more miles of roads, transmission lines and pipelines to service this exploration and production. Wind energy, as opposed to oil and gas, can be deliberately developed on sites that are already disturbed (i.e., mines, agricultural fields, industrial sites, etc.) due to the widespread availability of wind resources (Kiesecker et al. 2011). Oil and gas, with highly localized below-ground resources, is less adaptive, but the technological advances in directional drilling may allow more flexibility in siting of pads to avoid ecologically sensitive areas (Molvar 2003).

Habitat Fragmentation

Compared to other energy sources such as hydroelectric or coal, oil, gas and wind require less infrastructure but result in higher levels of habitat fragmentation because impacts are geographically scattered rather than concentrated (McDonald et al. 2009). Despite repeated mention in the literature, data on habitat fragmentation as a result of wind energy development is scarce (Arnett et al. 2007; NRC 2007). In Europe, the loss of habitat and habitat fragmentation associated with wind energy facilities is considered a greater impact than avian mortality from collisions (Gill et al. 1996).

Research on the implication of habitat fragmentation from energy sprawl has focused almost exclusively on birds and ungulates. Fragmentation in natural gas fields and from power lines has caused decreased lek attendance and increased avoidance in prairie-chickens

(*Tympanuchus* spp.) and greater sage-grouse (*Centrocercus urophasianus;* Doherty et al. 2008; Pruett et al. 2009). Declines in sagebrush obligate songbirds in Wyoming have been attributed to increasing oil and gas well densities (Gilbert & Chalfoun 2011). Similar impacts are expected from wind development, but no data exist (Johnson & Stephens 2011).

Several studies demonstrate adverse effects on ungulates from fragmentation due to oil and gas development. Mule deer (*Odocoileus hemionus*) failed to habituate to the presence of natural gas wells and exhibited altered habitat selection preferences as a result (Sawyer et al. 2006); pronghorn (*Antilocapra americana*) densities decreased near energy development (Easterly et al. 1991), and the population decline of many endangered woodland caribou (*Rangifer tarandus tarandus*) herds in Alberta is attributed in part to habitat loss and fragmentation from petroleum development (AWCRT 2005). In contrast, as of 2012, only one small-scale study in Oklahoma has investigated ungulate response to wind turbines (Hebblewhite 2011).

Given the lack of empirical data on the fragmentation impacts of wind energy on wildlife populations, development placement and design decisions are being made based on known impacts from other land uses such as petroleum development, transportation infrastructure or exurban sprawl. Aerial imagery could be a powerful tool for calculating a comparable metric of habitat fragmentation between energy developments, and across alternative types of energy production (Figure 5).

Noise and Light Pollution

Noise and light pollution can contribute to habitat degradation and wildlife displacement through disturbance and by masking auditory and visual life-history traits essential for survival and reproduction (Barber et al. 2010). The loudness of the noise or brightness of the light is less important than the consistency of both types of pollution. For instance, wildlife may habituate to a loud, consistent noise, but may avoid a quieter, less consistent noise that breaks the natural silence at irregular intervals.

Sources of noise within an oil and gas field include vehicle traffic, drill rigs, hydraulic fracturing operations, pump jacks, aerial coolers, compressors, flare stacks and generators. Normal noise levels from common construction equipment range between 70 and 96 decibels (dB) as measured at a distance of about 15 meters (m; FHWA 2006). During drilling and production, noise estimates in oil and gas fields range from 59 dB at drilling rigs to 70 dB at large gas compressors (interpolated to 15 m; G.L. Patricelli & S.L. Hooper, pers. comm.). Wind turbines create aerodynamic noise from the blades passing through the air, and noise propagation is positively associated with wind speed. A modern industrial scale wind turbine may reach a maximum noise level of about 78 dB at 15 m (Rogers et al. 2006). However, the impact of this noise can be tempered by the sound of the wind. Other sources of noise at a wind energy facility include temporary construction activities, vehicle traffic, and noise associated with the substation and operation buildings.

Night time light propagation from oil and gas fields in the intermountain west is limited to gas flares, vehicle headlights and temporary disturbance from 24-hour drilling barracks, which is in contrast to oil and gas development in other regions (e.g. Alaska’s North Slope) where artificial light is generally more common. Conversely, some utility-scale wind turbines must be lit to comply with Federal Aviation Administration requirements. The number of turbines lit varies at wind facilities based on numerous factors including location and topography.

Noise and light pollution are established sources of disturbance to biodiversity; however, reliable noise and light propagation data from both energy types are not available. Recently developed spatially explicit models such as SPreAD-GIS (Reed et al. 2010) and NMSim (Wyle Research & Consulting) could shed light on the relative impacts of energy development on these types of pollution under different land-use/land-cover scenarios.

Invasive Species

Biological invasions can reduce species richness and biodiversity and cause severe impacts to ecosystem processes and human well-being (Pejchar & Mooney 2009). Invasive plants may compete with native species, alter disturbance regimes, result in subsequent introduction of non-native animals and reduce the quality of the land for secondary uses such as grazing and agriculture (Pimentel 2002).

Invasive and non-native plants may be introduced via various pathways during construction of energy developments. Vehicles may transport non-native propagules, soils brought on-site may be infected with weeds and reseeding activities often result in the inadvertent introduction of invasive plants. Also, the presence of freshly disturbed soils and continued use of roadways perpetuates the risk of invasions for years after construction (Brooks 2007). Best management practices are often employed in both industries (wind and oil/natural gas) to prevent the introduction of invasive species and control invasives if establishment occurs. Empirical data regarding the presence/absence and degree of infestation in energy developments is limited and the few monitoring efforts are often proprietary in nature. Despite this, it is possible to use proxies (i.e., road length, area of temporary disturbance, etc.) combined with empirical data to estimate the extent of existing invasions or predict the invasibility of a proposed development.

Carbon Sequestration

A widely espoused benefit of wind energy is its substantial savings in greenhouse gas emissions, including carbon dioxide. Carbon sequestration is the process of soils and plants removing carbon dioxide from the atmosphere and storing it as a result of photosynthesis (McNeely 2009); thereby regulating the atmospheric concentrations of carbon dioxide which affect climate globally. The replacement of vegetation and top soil by impermeable surfaces associated with energy development reduces the potential for natural carbon sequestration and increases carbon emissions through the loss of biomass and increased soil erosion (Bruce et al. 1999). The extent to which energy development affects carbon losses from vegetation and soils is not clear. In light of global climate change, understanding the impact of these losses on the overall emissions debt of energy development is crucial for evaluating the relative "greenness" of alternative sources of energy.

Water Resources

Water resources, or the quality and quantity of water available to aquatic ecosystems and human consumption can be adversely affected by the development of oil, natural gas and wind energy facilities. The direct loss or consumption of water associated with wind energy construction and operation is relatively small. Some oil and gas wells, however, may require between two and seven million gallons of source water during the drilling process (Entrekin et al. 2011). Water is used as a lubricant during drilling and may be re-injected during a process known as "secondary recovery" which requires the injection of water or other liquids to increase pressure and improve well productivity.

Advances in horizontal drilling technology and hydraulic fracturing ("fracking") have helped to expand natural gas production. Fracking has unlocked natural gas supplies in shale and other unconventional formations across the country; however, the process requires large volumes of water. As the use of fracking has grown, so have concerns about its environmental impacts. Paramount is the concern that fracking fluids used to fissure rock formations contain numerous chemicals that could harm the environment, especially if they enter water supplies. Since natural gas is seen as a potential bridge to a low carbon economy it will be critical to assess freshwater impacts resulting from increased use of fracking (Entrekin et al. 2011).

Energy development results in impervious surfaces that prevent the infiltration of water into the soil. Greater runoff contributes to the degradation of riparian areas through increased sediment load, interferes with the natural processing of pollutants and reduces the amount of groundwater available to natural and human communities. As the area of impervious surface increases, native species richness and abundance tends to decrease and human adapted and invasive species increase (Hansen et al. 2005).

Oil and gas development likely causes greater impacts to water resources than wind energy development due to the large volume of water used during the drilling process and potential contamination of water resources. The impact of this water use on downstream ecosystems and human communities is not well understood. Particularly in the western U.S., both petroleum and wind development are expanding rapidly in arid regions, making the question of to what extent alternative forms of development impact water quality and compete for water with other users extremely relevant.

CONCLUSION

The goals of energy development and conservation need not be mutually exclusive, but they will require a sea change in how we think about and plan development. Proactive thinking about how to avoid siting conflicts, maintain biodiversity, and determine suitable mitigation responses will be critical. This approach will also require greater investment in offsets (compensating conservation actions) to address residual project impacts and deliver net gains for nature (Kiesecker et al. 2009). To meet this challenge, public land managers, private landowners and policy makers need more complete information on the impacts of energy development to guide decisions. Much of the existing research is species or location specific, which is locally useful, but does little to set regional, national or global science and policy agendas based on quantifiable impacts comparable across industries (Johnson & St. Laurent 2011). An understanding of the full suite of trade-offs between alternative energy development scenarios that incorporates local and landscape level impacts and can be applied to populations, communities, and ecosystems, is needed to make informed policy decisions.

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

1. Improve the quality, quantity and transparency of pre- and post-construction environmental impact assessments.

Understanding which species or populations are at particularly high risk from energy-related mortality requires clear and rigorous standards for pre- and post-impact studies (Garvin et al. 2011), better access to existing data, and a broader focus on all potential sources of mortality (Piorkowski et al. 2012). Regulations on both public and private lands should increase the requirements for post-development monitoring that focuses on quality rather than economy. A focus on species or communities of concern is important, but an ecosystem approach may be more appropriate. There should be a greater emphasis on indirect impacts to wildlife, which may be just as detrimental, over the long term, as direct mortality. Establishing a consistent monitoring network across energy projects will provide the foundation for innovative research that integrates engineering with ecology to minimize impacts on biodiversity and allow for comparisons between facilities.

2. Adopt a landscape scale approach to assessing impacts on biodiversity and ecosystem services.

The scientific and regulatory communities require a better understanding of how the indicators described above affect populations, ecosystems and society. Because location and species-specific studies are not practical for every new energy project, I recommend complimentary analyses that quantify the impacts of energy development on indicators at a landscape scale. Understanding the characteristics of the landscape that increase or decrease disturbance will aid in responsible design of projects at a regional scale and result in more comprehensive impact estimates. This type of analysis is relatively inexpensive and allows investigators to draw inferences over a larger geographic scale and for a wide selection of predictor variables. Examples include:

   a. Use aerial imagery to obtain accurate measurements of the habitat loss and fragmentation resulting from energy development across a diversity of landscapes. Incorporate existing data layers, development plans, and landscape characteristics to obtain estimates of the impacts of energy sprawl under alternative land-use scenarios.
   b. Model the propagation of noise and light pollution from sources in energy developments and identify the landscape characteristics (i.e., topography, elevation, land cover, etc.) that may affect these sources of disturbance.

c. Predict the spread of invasive species through the presence of linear rights-of-way and areas of temporary disturbance. Using empirical data, expert knowledge and landscape characteristics, invasion potential can be predicted for different developments, thereby allowing managers to focus efforts in high-risk areas.
d. Changes in water quality/quantity and carbon storage/sequestration as a result of energy development have been largely overlooked. Understanding how impacts to ecosystem services vary in magnitude is critical for decision-makers evaluating the tradeoffs of various development scenarios.

3. Assessing the cumulative impacts of energy development.

As energy sprawl spreads concurrently with human population growth, understanding the cumulative impact of all anthropogenic disturbances on natural ecosystems and human communities is emerging as core to the persistence of biodiversity and natural capital. It is the responsibility of our land and resource management agencies (i.e. Bureau of Land Management, Fish and Wildlife Service, Forest Service and state wildlife agencies) to incorporate the best possible science into development decisions and to make these decisions in such a way that they are explicitly taking cumulative impacts into account. Academic and other research scientists should work with regulatory agencies to fill the most pressing knowledge gaps and encourage rigorous pre- and post-construction studies that help identify best practices for avoiding, minimizing and mitigating impacts. Adopting the research and management directives outlined above could provide the tools necessary to safe-guard our natural heritage and preserve the ecological systems on which we depend.

When the average person consumes energy, they rarely think about the collective impact of this use which often leads to the overexploitation of limited resources. I argue that scientists can play a key role in making the connection between flipping a light switch and altering a landscape more explicit to policy-makers and the public. Energy sources should be evaluated based on metrics that go far beyond emissions. More comprehensive comparative studies of the true costs and benefits of alternative forms of development could provide the public with information on how energy development affects what they value; whether species rich communities, the natural beauty of open space, or clean and abundant drinking water. This level of transparency in our collective understanding of energy sprawl could catalyze more widespread and better informed support for thoughtful energy policy.

CHAPTER TWO

ENERGY SPRAWL: DIRECT AND INDIRECT IMPACTS ON BIODIVERSITY AND ECOSYSTEM SERVICES IN THE ROCKY MOUNTAIN WEST

INTRODUCTION

Global changes in energy production are occurring as a result of increased demand for clean, cheap and domestic power coupled with rising consumption and a diminishing supply of fossil fuels. Wind energy is at the forefront of this transformation and is currently the fastest growing source of electrical power. The benefits of wind energy include low lifecycle emissions of greenhouse gases (Jacobson 2008) and negligible air pollution (Arnett et al. 2007), making it a 'clean' alternative to fossil fuels such as oil and natural gas. However, this assessment ignores the impacts of 'energy sprawl', or the land-use required for energy production (McDonald et al. 2009). The degree to which wind energy and traditional sources of energy (e.g. oil and natural gas) contribute to energy sprawl and result in negative impacts to biodiversity and ecosystem services is not well understood (Figure 2).

Energy demand in the U.S. alone recently topped 99 quadrillion Btu (EIA 2009) and is expected to increase another 20% by 2030 (EIA 2009). Social, political and environmental pressures are promoting wind energy and other domestic and renewable power sources as an alternative to fossil fuels. In fact, the U.S. Department of Energy (DOE) has set a goal of achieving 20% of electrical power from wind by the year 2030 (DOE 2008). Already, wind energy production has increased fifteen fold since 2000 and is the world's fastest growing source of electricity (EIA 2011a). As a result of these trends, combined with the growing demand for oil, natural gas and coal, the influence of energy sprawl on the American landscape is expected to spread rapidly. Estimates suggest that by 2030 an additional 206,000 square kilometers (km) of land area will be directly impacted in order to meet U.S. energy demands (McDonald et al. 2009).

Empirical research on the impacts of energy sprawl on biodiversity and ecosystem services is scarce, inconsistent (McDonald et al. 2009; Johnson & St-Laurent 2011) and unevenly distributed among energy types and faunal groups (Figure 2). The majority of the wind-wildlife conservation literature is focused on direct impacts such as avian and bat collisions with wind turbines (Stewart et al. 2007). The majority of oil and natural gas related literature in western North America has focused on habitat degradation impacts to only a few species of concern: primarily ungulates and greater sage-grouse (Doherty et al. 2008; Holloran et al. 2010). The impacts of energy development on other important characteristics of the natural and built landscape, such as biological invasions, carbon sequestration, water resources and noise and light pollution are of great concern to society, but have received very little attention in the literature (Figure 2).

Measuring the impacts of energy development on plants, animals and ecosystems is traditionally accomplished through place-based field work, but this research is arduous, expensive, and sometimes impractical at the scales or time frames that matter for decision making. Local-scale field work must be complimented by landscape-scale assessments in order to evaluate and predict impacts on the spatial and temporal scale needed to guide land-use planning and management decisions. The use of indicators as surrogates for biodiversity measurements have proven to be effective tools for efficient research and planning at multiple scales (Milder et al. 2008), and aerial imagery and geospatial data can be used to remotely quantifying these indicators over large areas and through time (Lienwand et al. 2010).

The following indicators (Table 1), which have been shown to affect biodiversity, can be directly or indirectly measured from aerial imagery and used to assess net conservation impacts (Milder et al. 2008). Habitat loss and fragmentation are generally regarded as the leading causes of biodiversity loss (Wilcove 1987; Pimm & Raven 2000) and are easily digitized and quantified from aerial imagery. Although habitat loss is a species specific term, for the purposes of this study it is used to describe any natural vegetation removal due to human activity. Wildlife mortality from various sources (e.g. turbines, roads, power lines) associated with energy development impacts local populations and has the potential to affect communities and ecosystems (Fahrig et al. 1995). Noise and light pollution are quantifiable forms of habitat degradation which have diverse impacts on biodiversity and human communities (Barber et al. 2010; Beier 2006). Invasive species are the second greatest agent of species endangerment (Wilcove et al. 1998). Although the presence and extent of invasive plant cover is rarely visible from imagery, the relative extent of invasion potential can be estimated based on the amount and type of human activity (Gelbard & Belnap 2003). Finally, it is particularly important to understand impacts on ecosystem services such as carbon stock and water resources from energy development in light of climate change and diminishing supplies of freshwater. Geospatial estimates of biomass carbon stock are readily available (Ruesch & Gibbs 2008), and water consumption and loss can be estimated from energy infrastructure and the extent of impervious surfaces (i.e., any material that prevents the infiltration of water into the soil; Arnold & Gibbons 1996).

The indicators listed above (and in Table 1) act as surrogates for biodiversity and ecosystem services based on the assumption that, for instance, an increase in mortality, fragmentation or noise pollution reduces biodiversity (Fahrig et al. 1995; Stone 2000; Wilbert et al. 2008) and negative impacts to carbon and water adversely affect the ecological services they provide (Bruce et al. 1999; Hansen et al. 2005). An advantage of this approach is that indicators can be selected based on the strength of ecological principles and existing spatial data in ways that build on previous studies but retain the flexibility to be refined over time (Theobald et al. 2000; Theobald et al. 2005). These indicators are particularly well suited for evaluating the nature and extent of energy sprawl because they respond directly to changes in land-use and these changes are detectable immediately, whereas changes in species richness and abundance may display significant lag times (Saunders et al. 1991; Theobald et al. 2005; Milder et al. 2008). In addition, this approach is more practical for evaluating impacts over large geographic areas and can be scaled appropriately to address various environmental problems.

This study combines the use of aerial imagery, geospatial data and the indicators of biodiversity and ecosystem services described above in order to rapidly assess impacts from energy development. My objectives are to 1) compare the impacts of oil and gas development to wind energy development, 2) compare the impacts of both energy types to other land-uses, and 3) identify how characteristics of the landscape affect the level and intensity of the impacts. In contrast to a life-cycle analysis, which generally includes transportation, transmission and energy conversion (Martinez et al. 2009), this study specifically responds to emerging concerns over the impacts of energy sprawl and thus is limited to the farm or field where production occurs.

METHODS

Study Area

The study area was defined as the political boundaries of Colorado and Wyoming, U.S.A. These two states were chosen because they exemplify areas with substantial historic, current and potential future wind, oil and natural gas development. The location of all existing wind turbines in Colorado and Wyoming were obtained from the U.S. Geological Survey (USGS; O'Donnell & Francher 2010; Carr et al. 2011). Various operators and developers supplemented this data to ensure a complete census as of 11 September 2011. I then buffered the locations of all wind turbines in both states by 500 m and dissolved these into one layer. The locations of all current and historic oil and natural gas wells were downloaded from the Colorado Oil and Gas Conservation Commission (COGCC; 2011) and Wyoming Oil and Gas Conservation Commission (WOGCC; 2011) on 11 September 2011. I also buffered the locations of all oil and natural gas wells by 500 m and dissolved these into one layer. The wind turbine layer was then used to erase all areas coincidental with the oil and gas layer, and both layers were then used to erase all overlapping areas within the study area. The resulting feature class included three separate, features representing 1) wind energy, 2) oil and natural gas and 3) all remaining, non-energy areas, denoted as the 'reference' stratum. Sampling and data collection was completed with ArcGIS Desktop 10 software and all geospatial data was projected to North American Albers Equal Area Conic, North America Datum 1983.

Sampling Design and Data Collection

A total of 375 stratified (125 per strata), spatially balanced, simple-random 1-km diameter plots were selected from within the three feature classes (Figures 6 and 7). Within each sample plot I digitized the human "footprint" (i.e., any area directly affected by human activity) based on color imagery from the National Agriculture Imagery Program (NAIP) and supplemented this with Google Earth imagery when necessary. In spring 2012 I field mapped any energy infrastructure that was constructed since the most recently available imagery. The boundaries of areal features were digitized as polygons and linear features as polylines. Point features were used to denote noise and light sources, meteorological towers, waste pits, evaporation ponds, turbines and well heads. Each digitized feature was classified by land-use type (i.e., wind, oil and gas, agriculture, residential, etc.) based on a classification scheme slightly modified from Leinwand et al. (2010: Table 1). Each polygon and polyline was classified using Land Based Classification System (LBCS) feature types (LBCS 2006). Additional attributes assigned to each feature included the sample plot identification number, whether it was impervious to water or not (e.g. any non-vegetated surface), width (polylines only) and area (calculated automatically). Agricultural fields and croplands were considered a human footprint (Koellner & Scholz 2008) and were therefore digitized, whereas pastures and rangeland were not (Kiesecker et al. 2011). Fence lines and footpaths were also not digitized. Water bodies created by dams or other anthropogenic barriers were classified as a human footprint, whereas natural water bodies were not.

Landscape Characteristics

Each sample plot was characterized by the following covariates: dominant land-use, dominant land cover, dominant land owner, state, elevation, topographical ruggedness, median household income and housing density. The dominant land-use type was determined based on the greatest area of modification caused by a specific land-use type (other than wind or oil and gas) or, if no modification was present, visible signs indicative of a certain land-use type. I considered features immediately surrounding the plot in determination of land-use type and Google Earth was used where higher resolution images were available. I defined ‘undeveloped’ as plots in which there was no human footprint and no other visible sign of land-use. Due to low sample sizes determined during analysis, land-use type was categorized by agricultural, undeveloped and ‘other’, to represent all remaining land-use types. The dominant land cover was the type with the greatest surface area coverage within the plot. I obtained land cover types from the National Land Cover Dataset circa 2001 (NLCD; Fry et al. 2011). The dominant land owner within each plot was also determined by the greatest surface area coverage within the plot. Land ownership within Colorado was determined from the Colorado Ownership Management and Protection database (COMaP v9; Lavender et al. 2011) and Wyoming ownership information was obtained from the Bureau of Land Management (BLM), Wyoming state office (BLM 2011). I determined the average elevation within each plot by calculating the mean value of all 90 m cells from the National Elevation Dataset, Digital Elevation Model (DEM; Gesch et al. 2002; Gesch 2007). I assigned an index of topographical ruggedness to each plot equivalent to the standard deviation of the DEM values within each plot. The median household income was determined based on the 2010 U.S. Census at the block-group level (i.e., smallest geographical unit for which data is collected) and was obtained from ESRI's online services (ESRI 2011). Plots located within multiple block groups were denoted with the average median household income between all block groups within that plot. Finally, housing density was quantified using the Spatially Explicit Growth Model (SERGoM; Theobald 2005) and represented the mean housing density within each plot.

Indicators

In order to quantify impacts to biodiversity and ecosystem services, a set of eight unique indicators (i.e., response variables; Table 1) were selected as surrogates for empirical measurements. Habitat loss was calculated as the total area either temporarily or permanently affected by human activity within each plot. In order to quantify the degree of fragmentation within each plot, I found the mean Euclidean distance of all cells in the sample plot from the nearest direct habitat loss (GISFrag; Ripple et al. 1991). Therefore, low values represent higher levels of fragmentation (or less distance to habitat loss). Habitat loss used to measure fragmentation was digitized within a larger, 2-km diameter plot centered over the sample plot in order to account for disturbances located immediately outside (within 500 m) of the sample plot. Although the area of disturbance that is relevant to wildlife varies by species and other factors, numerous studies have indicated that, for many species, impacts are greatest within 500 m of disturbance (Burson et al. 2000; Gonzalez et al. 2006; Malo et al. 2011; Shanley & Pyare 2011). I calculated fragmentation levels resulting from wind energy, oil and natural gas and other land uses separately, as well as in combination.

Unique sources of wildlife (i.e., avian and bat) mortality from wind energy include turbines and meteorological towers (Erickson et al. 2005). Sources of mortality limited to oil and natural gas fields include evaporation ponds and waste pits (Ramirez 2010). Evaporation ponds are centralized, long-term facilities where the liquid byproduct of production is stored and separated from various chemical components. Waste pits serve the same purpose, but are temporary (usually less than one year) and associated with drilling. Evaporation ponds were identified from aerial imagery and it was assumed a waste pit was present at each well (S. Ellsworth, personal communication). In addition, I calculated the total length of roads and power lines within each plot.

Noise sources were identified from aerial imagery, wind turbine data and COGCC or WOGCC oil and natural gas well data. The average reported dB level of each noise source is listed in Table 2. I calculated the cumulative noise level within each plot by adding the decibel level of each noise source using the following equation:

$$L_{pt} = 10\log_{10}[\sum_{i=1}^{n}\log^{-1}(L_{pi}/10)]$$

where L_{pi} is the dB level for source i and L_{pt} is the total or cumulative noise level in the plot (Engineering Toolbox 2012). The majority of light sources were identified through aerial imagery; however, light sources from wind turbines were identified from the Federal Aviation Administration (FAA) obstruction database. Because detailed characteristics of light sources are not available, each known or potential light source was considered for the purposes of this study to have an equivalent impact.

In order to assess the potential for the introduction and establishment of invasive species I quantified two key sub-indicators. First, the total length of all linear features (i.e., roads, power lines, buried pipelines; indicator 6a) was quantified to represent human access to each plot. Second, I quantified the area of visible temporary (i.e., generally non-impervious, non-cropland) disturbance (indicator 6b) within each plot. This represents disturbed areas where invasion could occur and areas where reclamation activities may have inadvertently introduced weeds.

Biomass carbon stock values were estimated from data provided by Ruesch and Gibbs (2008) which is based off IPCC (2006) methods. I matched vegetation types listed in Ruesch and Gibbs (2008) to NLCD land cover types. The total area of each land cover type was reported for each plot as well as each digitized impervious feature. This information was used to calculate the total biomass carbon stock in each plot, as well as the total biomass carbon stock lost due to impervious surfaces.

In order to assess the relative impacts to water resources, the magnitude of water loss (indicator 8a) and area converted to impervious surfaces (indicator 8b) were estimated for each sample plot. Because water usage per well is either not reported or is proprietary information, water usage per well was estimated based on available information (Mielke et al. 2010; COGCC 2012). Impervious surfaces contribute to hydrologic changes that degrade waterways, prevent natural pollutant processing by preventing percolation and serve as a conveyance system for pollutants and runoff (Arnold & Gibbons 1996). The total area of impervious surfaces, as determined from aerial imagery, was calculated within each plot.

Data Analysis

Data recorded during the digitizing process were stored in an ArcGIS 10 file geodatabase and statistical analysis was completed in SAS 9.3 (SAS Institute 2010). Data were evaluated on a per plot basis in one of three forms for each unique indicator: 1) the change in impacts due to energy development, 2) the percent change in impacts relative to the predevelopment landscape, and 3) the sum of impacts from all land-use types. Data in the first and second form quantifies the change in impacts as a result of energy development and therefore uses only two strata, wind and oil and gas, which results in a sample size of 250. Data in the third form quantifies the total impacts in the plot regardless of energy or land-use type and therefore uses all three strata with a sample size of 375.

In order to meet my first objective, to compare oil and natural gas to wind energy, I used a parametric t-test to test for differences (alpha=0.05) between the mean per plot change in impacts and mean percent change in impacts for each indicator. To achieve the second objective, to compare impacts of energy development to other land uses, I used an analysis of variance which tested for differences between the three strata based on average cumulative impacts per plot. If a significant (alpha=0.05) difference was present, I tested individual *a priori* contrasts using Bonferroni adjusted alpha levels of 0.0167 (0.05/4) per test. The third objective, to assess the influence of covariates, was achieved using multiple linear regression and model selection techniques to determine how landscape characteristics influence the level and intensity of average cumulative impacts. For all analyses I first tested all nine covariates for normality and equality of variance. Because topography was based on the standard deviation of DEM elevation values, a logarithmic transformation of the topography metric was required to meet these assumptions. Subsequently, the covariates were tested for co-linearity and because no significant co-linearity was found, all covariates were carried forward for model selection. I used a best-subset technique to rank all 511 possible models (excluding interaction terms) by Akaike's information criteria (AIC; Burnham & Anderson 2002) using PROC REG (SAS 9.3). Because selection of a single 'best' model is unsatisfactory due to the variation in that model (Burnham & Anderson 2002), I instead ranked the relative importance of the parameters. First, I established a 90% confidence set for each indicator by adding all the top models until the sum of their Akaike weights was greater than or equal to 0.90. The relative importance of each parameter was determined by selecting all the models within the 90% confidence set where the parameter appears and finding the sum of the associated model probabilities (Anderson 2008). This technique was used to determine the most important parameters for each of the ten indicators and sub-indicators. The cumulative relative importance of each parameter, averaged across all ten indicators and sub-indicators, was used to rank the 'overall' relative importance of each covariate.

I also compared impacts per unit energy produced within each plot. The Btu is a comparable unit of measure between barrels of oil, cubic feet of natural gas and kilowatt hours of electricity. I chose to compare impacts per energy consumed by an average American in one year, or 317 million Btu (MMBtu; EIA 2011a). Although this assumes that a single person is able to obtain all their power from either only wind or only oil and natural gas and only within Colorado and Wyoming, the objective was to use a single unit of energy to demonstrate potential per capita impacts in a particular region. Production data for each wind energy facility is available from the EIA (EIA 2012) since 2001 and production data for each oil and natural gas well is available from the COGCC (2011) and WOGCC (2011) since 1999 and 1973, respectively. Mean annual production per plot was estimated from the available data and compared to the average impacts for each indicator per plot to estimate impacts per person.

RESULTS

I digitized a total of 6,763 unique point, line and polygon features within the 375 sample plots. Human activities impacted 6,561 ha (395 ha due to wind energy and 421 ha due to oil and gas), representing approximately 22% of the land area in all the study plots. In total, my sample plots captured 295 turbines (over 13% of existing wind turbines in Colorado and Wyoming) and 361 oil or natural gas wells on 235 well pads (approximately 0.17% of existing and historic wells in Colorado and Wyoming). The following sections present results of the impacts of energy sprawl on each of my indicators on a per plot and per unit energy basis.

Direct Habitat Loss and Fragmentation

Based on the impact of energy development alone, the average area of direct habitat loss per plot was not significantly different between wind and oil and gas (wind=3.09 ha, oil and gas=3.36 ha; $t=1.18$, $df=248$, $p=0.239$). However, oil and gas accounted for 70.9% (+/- 3.47 standard error [SE]) of all habitat loss per plot, compared to just 40.3% (+/- 3.80 SE) due to wind energy. Fragmentation levels were significantly higher for oil and gas than wind energy (wind=237.6, oil and gas=190.5; $t=-3.5$, $df=248$, $p<0.001$) and oil and gas increased fragmentation by 62% (+/- 2.74 SE), compared to 30% (+/- 2.48 SE) from wind energy (Figure 8). Further investigation revealed that fragmentation levels prior to energy development were on average 2.7 times higher in wind energy facilities than oil and gas fields and wind energy was three times as prevalent in plots where the dominant underlying land cover was cultivated cropland. Total habitat loss amongst the three strata, regardless of land-use or energy type, was significantly greater with wind energy than oil and gas (*F*[1,372]=44.58, p<0.0001) or the reference stratum (*F*[1,372]=55.36, p<0.0001). The pairwise comparison of oil and gas to the reference stratum was non-significant. Fragmentation in the reference stratum averaged 463.65 m (+/- 33.39 SE) to disturbance, significantly more than wind (114.1 m +/- 9.85 SE; *F*[1,372]=143.64, p<0.0001) or oil and gas (142.37 m +/- 8.0 SE; *F*[1,372]=121.99, p<0.0001). The pairwise comparison of fragmentation between energy strata was non-significant (Figure 8).

Potential Mortality

Wind energy plots averaged 2.36 (+/- 0.11 SE) wind turbines and 0.05 (+/- 0.02 SE) meteorological towers per plot. Oil and gas plots averaged 2.87 (+/- 0.27 SE) waste pits and 0.02 (+/- 0.002 SE) evaporation ponds per plot. The statistical differences between these were not tested due to inherent differences in features and a lack of reliable mortality rate estimates. Oil and gas averaged 1,354.4 m (+/- 86.14 SE) of road per plot, compared to 1,147 m (+/- 58.59 SE) for wind energy. Wind energy averaged 118.2 m (+/- 31.08 SE) of power line per plot, significantly more than oil and gas with only 15.61 m (+/- 9.1 SE; t=-3.16, df=248, p=0.0018). The presence of energy development on the landscape is correlated with significantly more roads than observed within the reference stratum (*F*[1,372]=92.23, p<0.0001), but the pairwise difference between energy types was non-significant. The pairwise comparison of average length of power lines between strata was not significant at α=0.0167 (Figure 9).

Noise and Light Pollution

Noise from wind turbines averaged 92.79 dB (+/- 1.91 SE) per plot, which was an average increase of 55.55 dB (+/- 1.37 SE) over pre-development conditions. Oil and gas development was significantly quieter (t=-21.37, df=248, p<0.0001), averaging 15.22 dB (+/- 3.09 SE) due to oil and gas infrastructure only; an increase of 7.73 dB (+/- 1.71 SE) per plot over pre-development conditions. Noise levels in both energy strata were significantly greater than in the reference stratum (*F*[1,372]=266.92, p<0.0001), as well as between the energy strata (*F*[1,372]=501.13, p<0.0001).

Wind energy is associated with ten times more light sources per plot than oil and gas (wind: 0.9 light sources, +/- 0.18 SE; oil and gas: 0.09, +/- 0.04 SE). However, compared to the reference stratum, energy developments are relatively dark, averaging significantly fewer light sources than the reference stratum (*F*[1,372]=7.17, p=0.0078). The pairwise comparison of light sources between wind and oil and gas was non-significant.

Susceptibility to Invasion

The surrogates used to assess susceptibility to biological invasion, length of linear features and area of temporary disturbance, were not significantly different between wind energy and oil and gas (linear: wind=1,903 m, oil and gas=2,509 m; t=0.78, df=248, p=0.4361; temporary: wind=1.40 ha, oil and gas=1.49; t=0.27, df=248, p=0.7882). On average, wind energy increased the length of linear features by 1,903 m (+/- 119.84 SE), or 78.4% (+/- 2.3 SE) and increased the area of temporary disturbance by 1.4 ha (+/- 0.16 SE), or 56.3% (+/- 4.0 SE). Oil and gas, on average, increased the total length of linear features by 2,509 m (+/- 134.95 SE), or 77.7% (+/- 2.3 SE) and increased the area of temporary disturbance by 1.49 ha (+/- 0.19 SE), or 63.2% (+/- 4.1 SE). Considering all land uses, the reference stratum had significantly less distance of linear features (*F*[1,372]=61.33, p<0.0001) and significantly less area of temporary disturbance (*F*[1,372]=12.11, p=0.0006). The pairwise comparison between energy strata for both linear features and temporary disturbance was non-significant.

Carbon Stock and Water Resources

The development of oil and gas resulted in approximately 15.8 tons (+/- 2.98 SE) of carbon lost per plot, significantly more than wind energy (7.43 tons +/- 0.7 SE; t=2.71, df=248, p=0.0071). However, wind energy was responsible for 84.0% (+/- 2.1 SE) of all carbon stock lost per plot, while oil and gas was only responsible for 75.5% (+/- 3.15 SE) per plot, indicating the importance of underlying land-use on carbon stock losses. Further investigation indicated that prior to energy development oil and gas plots had about 2.7 times the biomass carbon stock of the average wind energy plot. The oil and gas stratum was found to have significantly more biomass carbon loss than both the wind energy (F[1,372]=7.01, p=0.0085) and reference stratum (F[1,372]=6.04, p=0.0144) when considering all land uses.

Oil and natural gas development, although highly variable, requires significantly greater water usage than wind energy. The most common method of crude oil extraction in the U.S. is secondary recovery, which requires water flooding to stimulate production. This method uses about 62 gallons of water per MMBtu of oil extracted. Conventional natural gas extraction does not require water (Mielke et al. 2010). According to the COGCC, hydraulic fracturing, which has occurred in approximately 90% of oil and gas wells since the 1970s, uses about 1.6 million gallons of water per well (COGCC 2012), although other estimates range from one to five million gallons (Belanger 2012). Alternatively, wind energy requires essentially no water for construction or operation (Mielke et al. 2010). Applying these water usage estimates to the number and type of wells in the sample, an average of 4.6 million gallons of water per plot is consumed from oil and gas production each year.

The area of impervious surface created by energy development is not significantly different between wind and oil and gas (wind=1.71 ha, oil and gas=1.88 ha; t=1.08, df=248, p=0.2811). However, oil and gas development caused an average of 63% (+/- 3.8 SE) of the impervious surface per plot, significantly more than wind energy (37.8% +/- 3.8 SE; t=4.72, df=248, p<0.0001). There was also no significant difference between the three strata for the total area of impervious surfaces created (*F*[2,372]=0.29, p=0.7454).

Per Unit Energy Comparison

Total annual energy production per wind plot averaged 39,539 (+/- 1,800 SE) MMBtu and total energy production per oil and gas plot averaged 101,044 (+/- 20,446 SE) MMBtu. Production from oil and gas wells was highly variable, ranging from numerous wells with no production, to a single plot which averaged 1.4 million MMBtu per year. Conversely, per plot production from wind energy was far more consistent, but with a lower ceiling of 93,092 MMBtu per year at one particular plot. Impacts per unit energy were greater due to wind energy for all indicators except water consumption. For example, within my sample an average American would require approximately 247 m^2 (+/- 20.13 SE) of habitat loss to acquire their annual energy consumption from wind energy, but only 106 m^2 (+/- 22.56 SE) if that energy came from oil and gas. For all indicators, except water consumption, the impacts from oil and gas were between 3.9 and 83% of the impacts from wind energy, per unit energy produced (Figure 10).

Relative Importance of Covariates

As expected, energy type was determined to be the most ‘important’ parameter with a mean cumulative model weight of 0.74. Housing density, land cover and topography were also important parameters, while state, with a mean cumulative model weight of 0.35, was deemed least important (Table 3).

DISCUSSION

My results indicate that energy development is associated with a variety of direct and indirect impacts to indicators associated with native biodiversity and the provision of selected ecosystem services within Colorado and Wyoming. The impact of energy sprawl differed depending on the indicator quantified, energy type and the perspective of the comparison. In general, wind energy created more noise and light pollution, while oil and gas had greater impacts to habitat fragmentation, carbon stock and water resources. When controlling for other variables, the susceptibility to invasion and habitat loss were approximately equal between the two energy types. However, characteristics of the landscape, such as underlying land-use and land cover, were very important when considering the change in impacts due to energy development and when comparing the three strata.

Regardless of energy type, development in already disturbed areas (i.e., agricultural land such as cultivated crops) resulted in fewer impacts. Colorado and Wyoming have been proposed as two of 38 states where the DOE goals for wind energy development can be entirely met on disturbed lands (Kiesecker et al. 2011). Figure 11 shows the portion of the study area where wind energy development could occur on previously disturbed lands. The wind industry is relatively young and the characteristics of this energy source make it feasible to minimize habitat loss and reduce the impacts of fragmentation through strategic planning. Oil and gas development is typically less flexible due to the geographical restrictions of underground reserves. However, new technology which could utilize existing well pads to drill dozens of new wells has not been fully applied in Colorado and Wyoming (Molvar 2003). In both cases, given the rapid pace of energy sprawl, moving quickly to establish regulations or incentives to develop energy resources on already disturbed land may be one of the most important steps we can take to minimize impacts to biodiversity and ecosystem services.

This study further highlights the need for better post-construction mortality rate estimates. Using the best available turbine mortality rate of 1.78 birds and 2.13 bats per MW (Johnson & Stephen 2011), the average mortality rate per wind energy plot in my study is 6.3 birds and 7.5 bats per year (assuming an average of 1.5 MW turbine power and given the potential sources of mortality I was able to quantify using aerial imagery). However, Johnson and Stephen's (2011) estimate was based on only 21 existing wind facilities, only 2,194 MW of production and represents only a few geographic locations and land cover types. Due to the small sample size from which these data were extracted, and the likelihood that mortality varies in unknown ways with various landscape characteristics, it is problematic to infer annual mortality rates for my study area using these estimates. Unfortunately, mortality estimates related to roads, power lines and other sources are also relatively unknown and certainly have not been collected systematically in my study area.

The lack of robust mortality estimates (Kuvlesky et al. 2007; Stewart et al. 2007) speaks to the young and largely proprietary nature of energy-wildlife research which deters standardized protocols, information sharing and researcher access to facilities (Piorkowski et al. 2012). My research method is effective at identifying and quantifying potential sources of wildlife mortality; however, without reliable mortality rate estimates these figures hold little value. Mortality monitoring should be standard practice after the construction of every new wind facility so that our understanding of avian and bat mortality is based less on extrapolation and more on characteristics of the development and the landscape such as topography, land cover and meteorological conditions. Monitoring for mortality associated with oil and gas production is equally as important.

Although my results indicate that wind energy creates more noise pollution than oil and gas, the noise created by turbines is tempered by the sound of the wind. My analysis assumed a moderate wind speed of four to 6 m per second. However, with no wind, no noise is created by turbines and at high wind speeds much of the turbine noise is concealed by the sound of the wind and rustling of vegetation (Fegeant 1999). The impact of noise pollution on the natural and human landscape is dependent on numerous factors, many of which could not be quantified here. Improvements to the assessment of noise pollution would include the incorporation of multiple variables, such as geographic location, topography and atmospheric conditions, which can be readily modeled using GIS tools like SPreAD-GIS (Reed et al. 2010) and NMSim (Wyle Research & Consulting).

The amount of biomass carbon lost due to land-use change varies with the location of development and land cover type. Reducing the loss of biomass carbon could also be accomplished by locating development in previously disturbed areas. In this study, oil and gas development resulted in greater biomass carbon lost because it was associated with forested landscapes where there is approximately fifteen times more biomass carbon stock compared with grasslands and shrub lands (Ruesch & Gibbs 2008). The consumption of water due to energy development is based on characteristics of the industry and not of the landscape. Therefore, measures to address water use should be focused on the specific actions of the oil and gas industry and location of water sources. For example, hydraulic fracturing can open new natural gas supplies, but the process requires massive amounts of water and uses chemicals that could harm the environment (Entrekin et al. 2011).

I found that oil and gas results in fewer impacts per unit energy produced than wind energy. However, two important caveats deserve to be mentioned. First, it is unlikely that this relationship is linear. That is, impacts do not increase or decrease steadily in proportion to energy produced. Second, this result does not account for the impact of oil and gas over time. The average life span of both an industrial scale wind turbine and an oil and gas well is 20 years (Martinez et al. 2009; EnCana 2011). After 20 years the wind turbine can be replaced by a new turbine on the same pad with no additional impacts. However, after the oil or gas well runs dry, a new well would need to be drilled at a new location in order to maintain the productivity required to meet the demands of society. Although the sources of mortality, noise and light will be removed, water usage will stop and impervious surfaces will become permeable, habitat degradation from vegetation removal, fragmentation and the presence of invasive species may continue for many years. Reclamation is uncommon due to lack of requirements by various land managers and is particularly unsuccessful due to the harsh environment of the arid west. For this reason, one can expect the impacts to some indicators to double or triple through time with oil and gas, eventually surpassing those of wind energy, whereas these impacts remain steady with wind (Figure 12).

This research uses a novel approach to conduct a multivariate and large-scale assessment of impacts to indicators associated with native biodiversity and the provision of selected ecosystem services in a region increasingly dominated by energy development. Application of this study methodology has great potential in land-use planning, particularly for assessing cumulative impacts, comparing development alternatives, and long-term or large-scale planning. This study can be repeated in several to many years to assess land-use change or the application of strategic approaches to energy production such as Development by Design (Kiesecker et al.

2009). This study design can also be modified and scaled to meet specific objectives; for example, to predict the future, cumulative impacts of development on sensitive species such as greater sage-grouse, sage-brush obligate songbirds, or golden eagles (*Aquila chrysaetos*) in the intermountain west.

The eight indicators analyzed in this study are very important to wildlife conservation and human well-being; however, they are not equivalent for all taxa or human communities. It is not clear, for example, how the net losses associated with direct mortality compare to the indirect impacts of habitat loss at the local, regional or population scale. Additionally, although beyond the scope of this study, it will be important to understand how the impacts of climate change might interact with energy sprawl to synergistically influence biodiversity and ecosystem services.

Although this study and its results are a retrospective analysis of land-use in the intermountain west, the implications of this work go far beyond this region. First, this approach could be used to predict future impacts based on the geographic distribution of energy resources and the magnitude of demand. Second, showing how energy use by an average consumer impacts the landscape could be valuable for empowering citizens to make informed decisions and take meaningful actions. Ultimately, this novel technique and my specific findings can be used by developers, planners and policy-makers to plan energy development that balances the conservation of biodiversity with society's demand for energy.

TABLES

Table 1. List of indicators, predictor variable and covariates which were quantified, on a per plot basis, from aerial imagery and other spatial data sources and used to quantify impacts to biodiversity and ecosystem services in Colorado and Wyoming.

Indicators (Response Variables)	**Measures/Metrics (per plot)**
1. Direct Habitat Loss	Total hectares of direct and permanent or temporary habitat loss
2. Fragmentation	GISFrag: mean Euclidean distance to habitat loss
3. Potential Mortality	Total number of turbines, towers, evap. ponds and waste pits. Length of roads and power lines.
4. Noise Pollution	Cumulative decibel level
5. Light Pollution	Total number of artificial light sources
6a. Susceptibility to Invasion	Total meters of linear features
6b. Susceptibility to Invasion	Total hectares of temporary disturbance
7. Carbon Sequestration	Total tons of biomass carbon lost
8a. Water Resources	Gallons of water consumed
8b. Water Resources	Total hectares of impervious surface

Predictor Variable	**Potential Values**
Energy Type (Strata)	Wind Energy, Oil & Natural Gas, No Energy Development

Covariates	**Potential Values**
Land-Use Type	Agriculture, Undeveloped, Other (i.e., recreation, residential, industrial, mixed-use, etc.)
Land Cover	Developed, Forested, Shrub/Scrub, Grassland, Cultivated Crops
Land Ownership	Federal, State, Private, Bureau of Indian Affairs
State	Colorado, Wyoming
Topography	Continuous Variable (Standard Deviation of Elevation; range 0.7 – 166.2)
Elevation	Continuous Variable (Mean Elevation in Plot; range 1,100 to 3,800 meters)
Median Income	Continuous Variable (range: $24,658 to $92,675)
Housing Density	Continuous Variable (range: 0 to 7,688 housing units per 1,000 hectares)

Table 2. Reported average or normal noise levels (dB) of common noise sources associated with energy development, which were attributed to each digitized noise source.

Noise Source Type	Normal Decibel Level at 0 m	Source
Ambient Conditions (i.e., without mechanical noise)	20 - 60	Harrison et al. 1980
Buildings (including residential, small mixed-use, and operation/maintenance)	50	BLM 1992
Industrial Buildings and Apartment Complexes	80	BLM 1992
Center Pivot Irrigator	70	Lindsay Manufacturing, LLC
Generator	85.85	J.L. Blickley & G.L. Patricelli, unpublished data
Large Compressor	93.22	J.L. Blickley & G.L. Patricelli, unpublished data
Flare	100	Hantschk & Schorer 2008
Small Compressor	90.22	J.L. Blickley & G.L. Patricelli, unpublished data
Pumpjack	90.54	BLM 1992
Turbine (Industrial Scale)	90.58	Tonin 2012

Table 3. Relative importance of covariates as determined by their cumulative model weights for each indicator and mean cumulative model weights for all indicators. A parameter included in all models from the 90% confidence set would have a score of approximately 0.9 (+/- due to rounding).

		INDICATORS										
				Potential Mortality				Susceptibility to Invasion				
COVARIATES (Model Parameters)	Rank	Habitat Loss	Habitat Fragmentation	Roads	Power Lines	Noise Pollution	Light Pollution	Linear Features	Temporary Disturbance	Carbon Loss	Impervious Surface	Mean Cumulative Model Weights
Energy Type	1	0.91	0.91	0.90	0.62	0.90	0.37	0.90	0.90	0.35	0.63	0.74
Housing Density	2	0.91	0.78	0.31	0.90	0.90	0.90	0.90	0.32	0.33	0.90	0.72
Land Cover	3	0.91	0.28	0.31	0.60	0.90	0.76	0.26	0.90	0.80	0.63	0.63
Topography	4	0.91	0.34	0.37	0.27	0.90	0.71	0.23	0.90	0.90	0.80	0.63
Income	5	0.37	0.84	0.73	0.30	0.58	0.90	0.90	0.20	0.26	0.90	0.60
Elevation	6	0.22	0.91	0.86	0.21	0.86	0.25	0.55	0.26	0.24	0.44	0.48
Land Owner	7	0.29	0.91	0.23	0.36	0.59	0.25	0.54	0.53	0.69	0.38	0.48
Land-Use	8	0.63	0.91	0.61	0.54	0.30	0.26	0.79	0.22	0.27	0.24	0.48
State	9	0.30	0.21	0.28	0.22	0.27	0.30	0.64	0.24	0.80	0.23	0.35

FIGURES

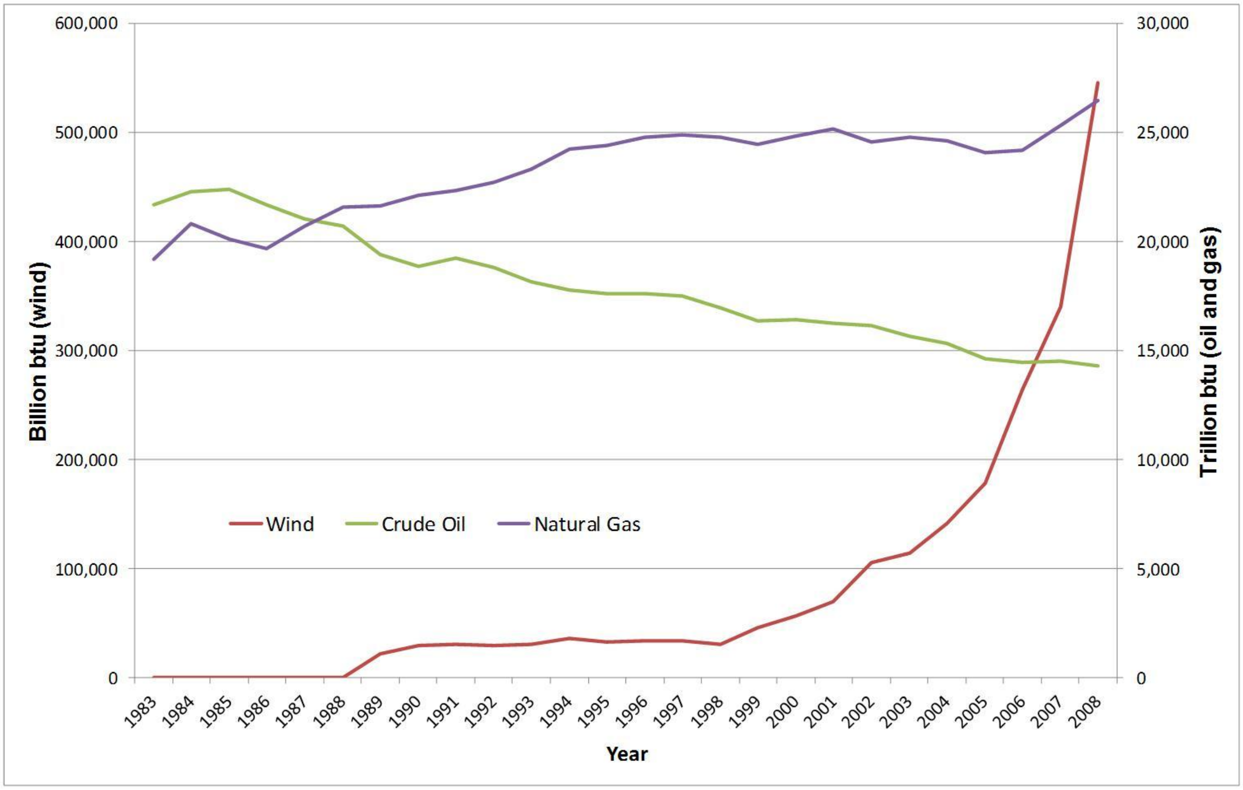

Figure 1. Annual production of wind, natural gas and crude oil in the U.S. between 1983 and 2008. Production is converted to Btu and shown in Billion Btu for wind energy and trillion Btu for crude oil and natural gas (EIA 2009).

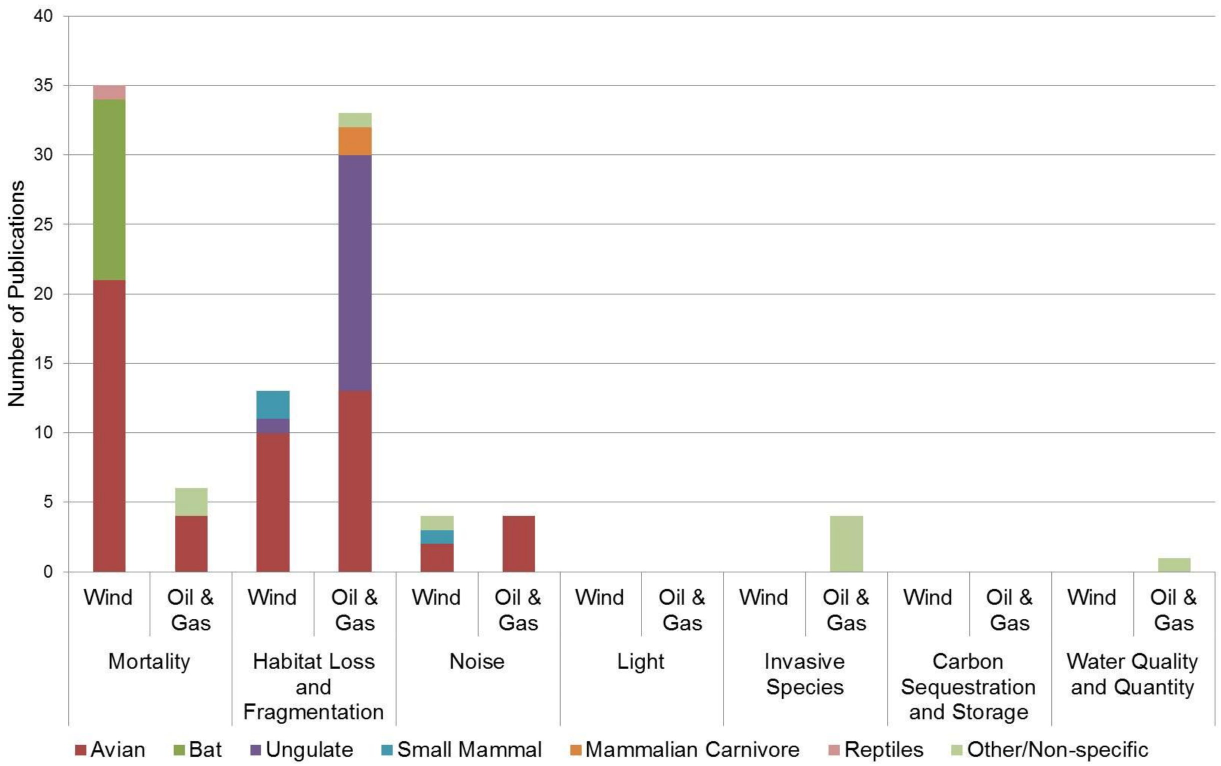

Figure 2. The number of published studies of wind, oil and natural gas development impacts on seven indicators of biodiversity and ecosystem services. Only articles with primary data on the impacts of onshore wind, oil or gas development were included. Articles were obtained from several recent reviews and books as well as a systematic web-based search using key words (indicators) and modifiers (energy type) in ISI Web of Knowledge (http://www.webofknowledge.com).

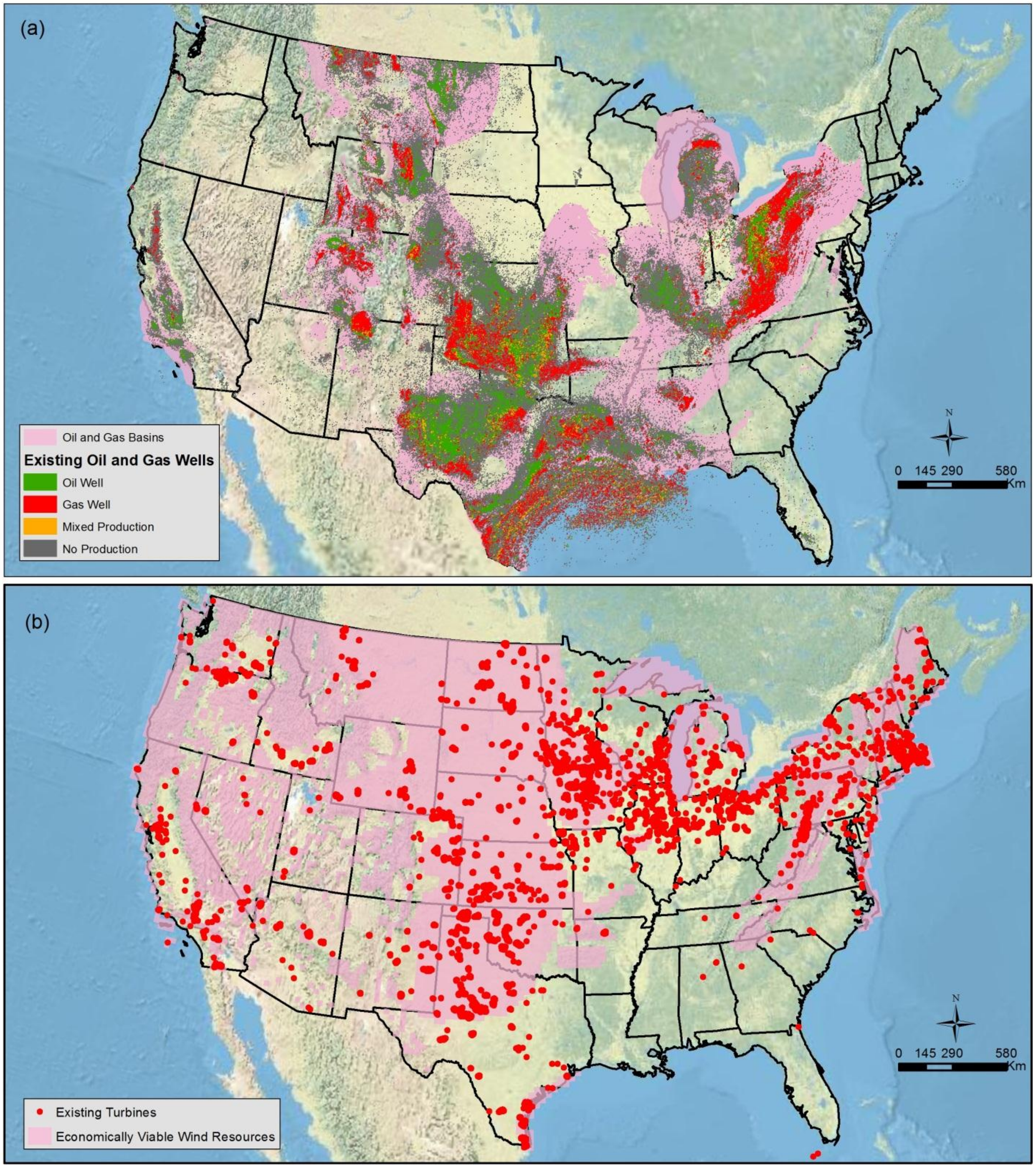

Figure 3. Existing and potential future expansion of energy sprawl in the contiguous U.S. (a) Existing oil and natural gas wells and areas with suitable geologic resources for future extraction (Biewick 2008; EIA 2011b). (b) Existing wind energy facilities and areas with suitable wind resources for industrial scale wind energy development (Elliott et al. 1986; FAA 2011).

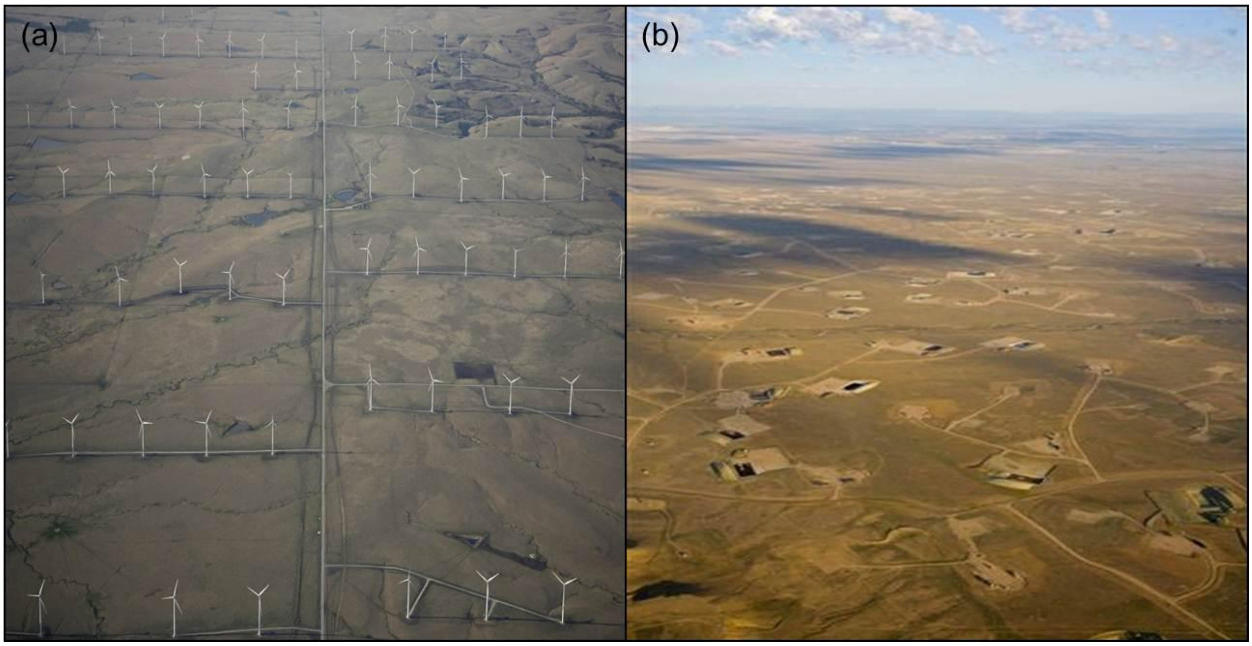

Figure 4. Characteristic images of energy sprawl on a western landscape. (a) Wind energy facility (Photo Credit: Michael Forsberg). (b) Natural gas field near Pinedale, Wyoming (Photo Credit: David Stubbs).

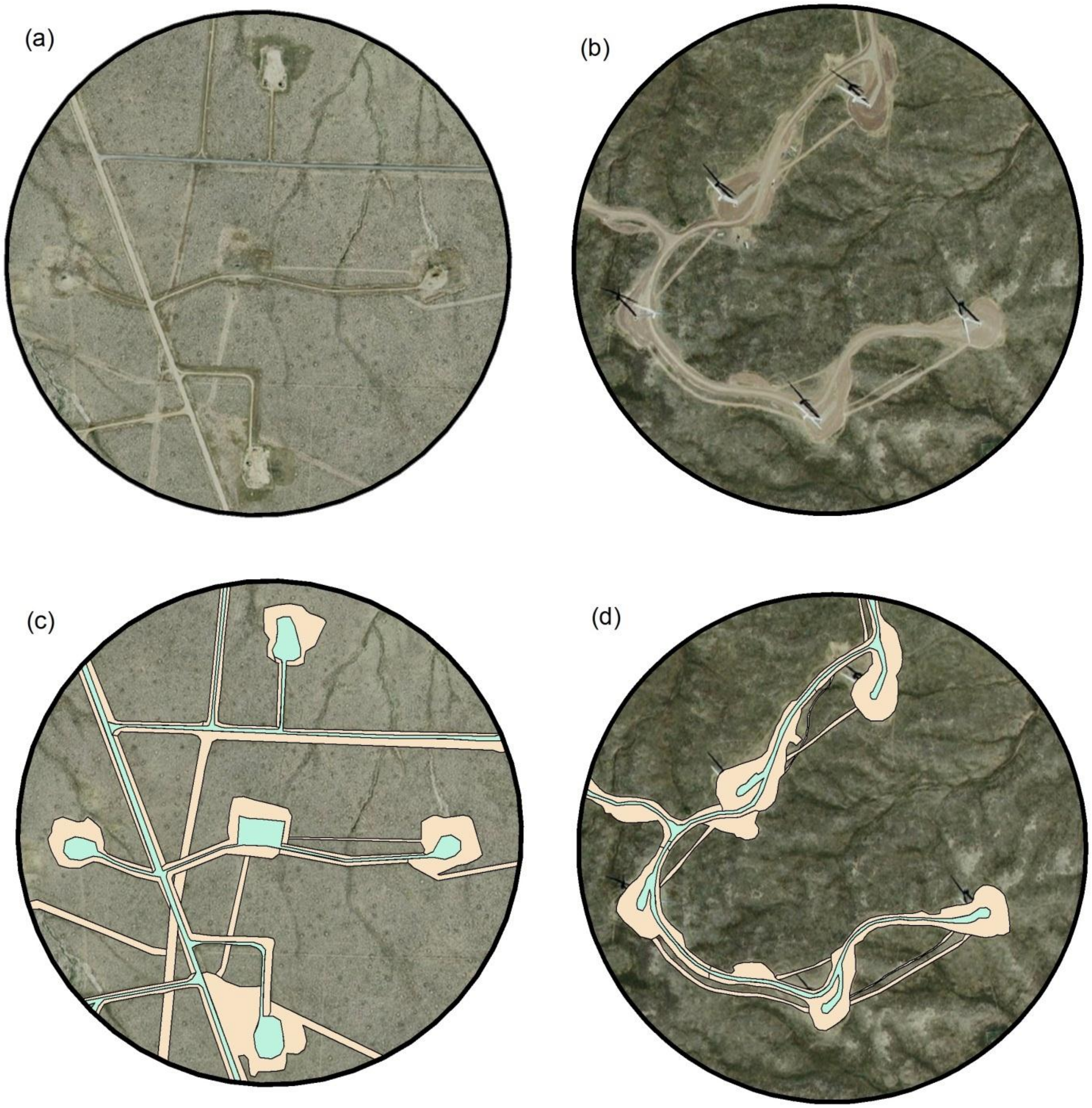

Figure 5. Aerial imagery of a natural gas field (a) and a wind energy facility (b). Each image includes five turbines/well pads plus associated infrastructure within a one km diameter plot. The environmental footprint of each site (a,b) is digitized using GIS (c,d). Blue polygons indicate permanent habitat loss and beige polygons represent temporary disturbance from construction. This information, paired with site-level data from these locations or similar areas, can be used to estimate relative impacts on indicators such as habitat loss, fragmentation, impervious surfaces, annual wildlife mortality, invasive plant infestation, changes in carbon stocks and impacts to water resources. *Note: the annual production of the five natural gas wells, measured in Btus, is approximately 2.6 times the production of the five wind turbines, thus energy production should also be taken into account when calculating the relative impact of alternative energy sources.

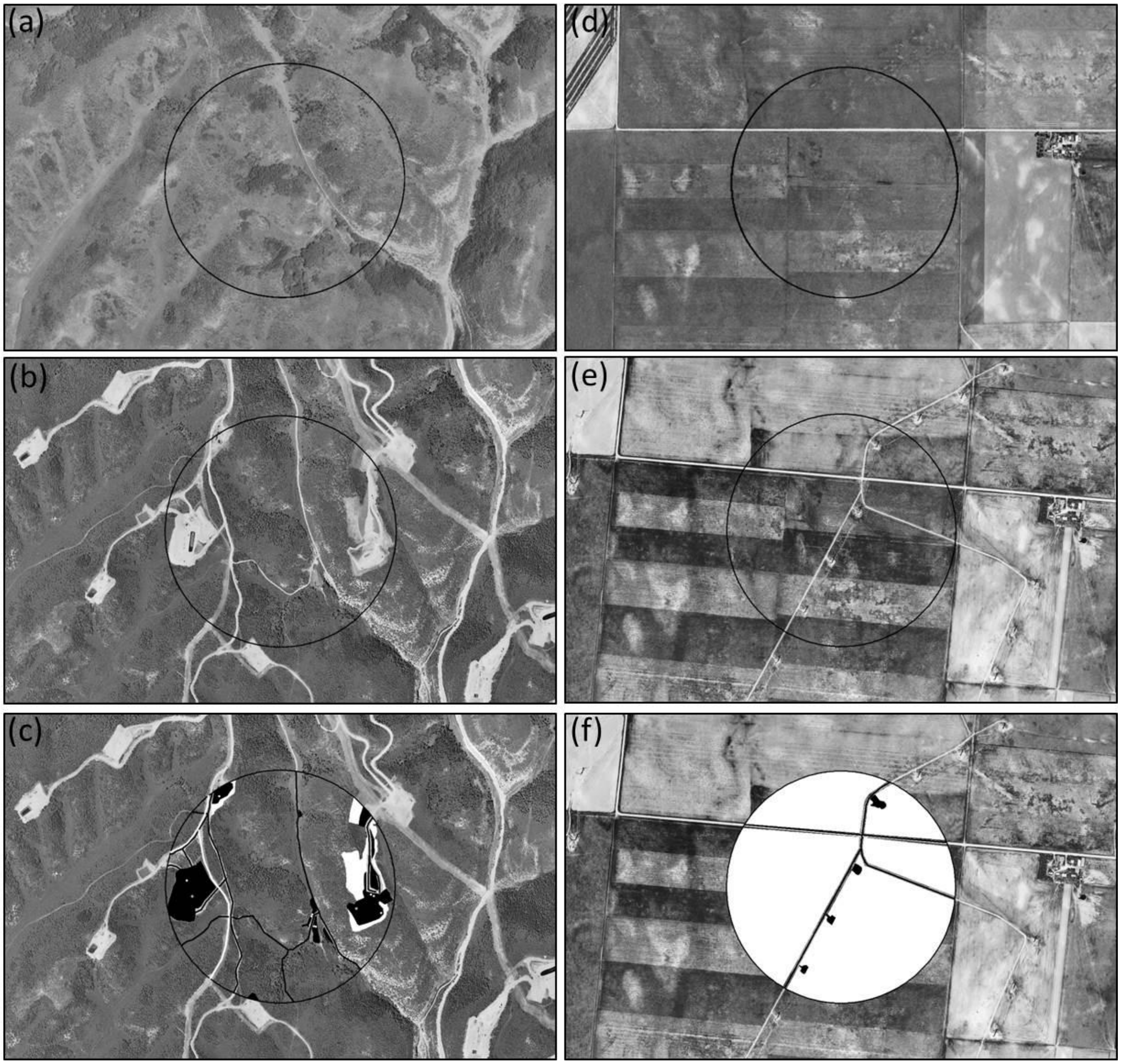

Figure 6. Examples of sample plots used to quantify impacts to indicators of biodiversity and ecosystem services. Western Colorado landscape before (a) and after (b) natural gas development. Eastern Colorado landscape before (d) and after (e) wind energy development. Sample plots with habitat loss digitized (c,f) as impervious (black) and non-impervious (white). Imagery from Google Earth (a,d) and NAIP (b,c,e,f), obtained on 18 August 2012.

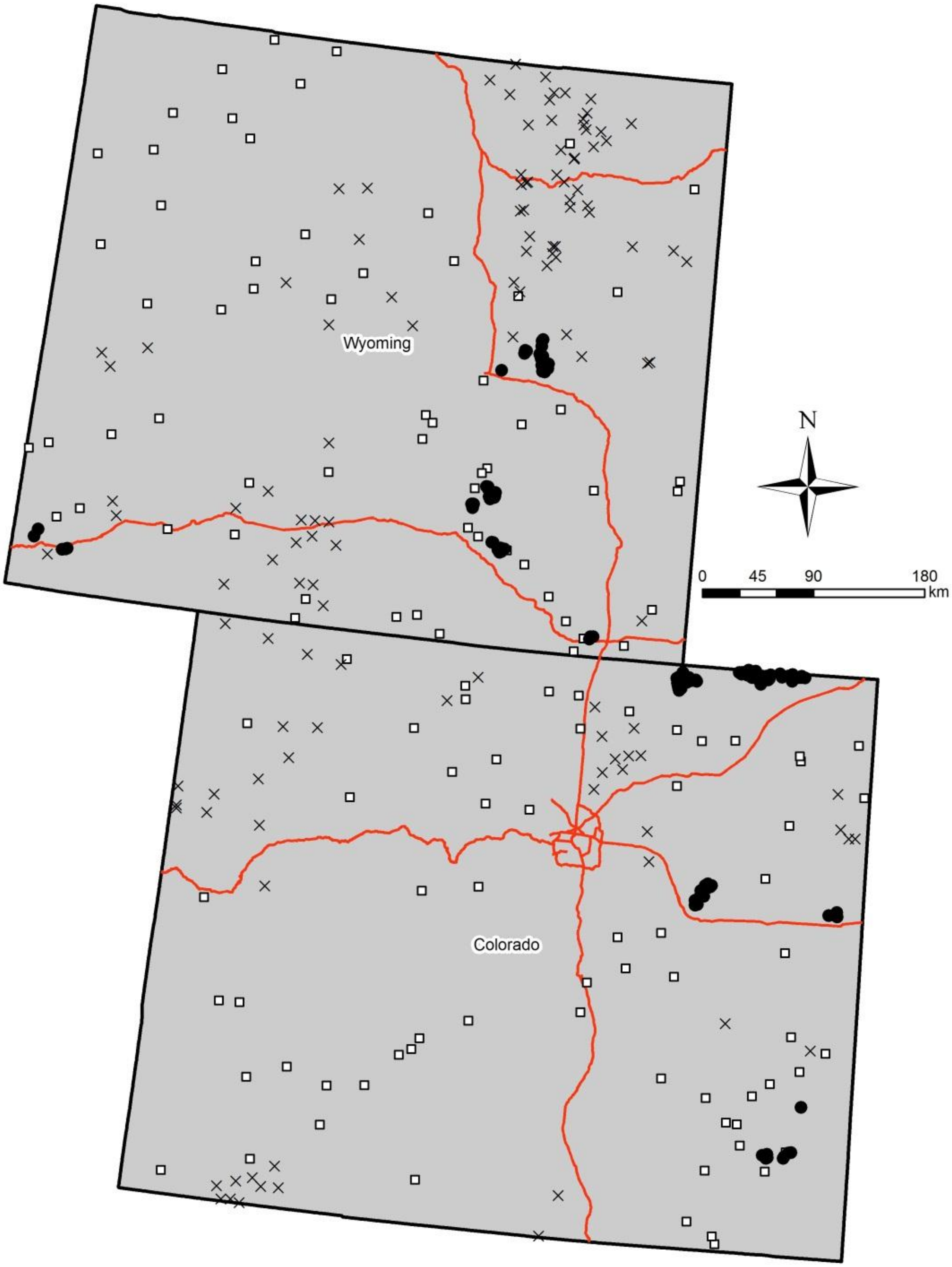

Figure 7. The study area, defined by the political boundaries of Colorado and Wyoming, which includes 375 stratified, randomly selected, 1-km diameter sample plots used to assess the impacts of wind energy and oil and natural gas development on indicators of biodiversity and ecosystem services. Crosses (X) are oil and natural gas plots, black circles (•) are wind energy plots and squares (□) are reference plots. Red lines represent major highways for reference.

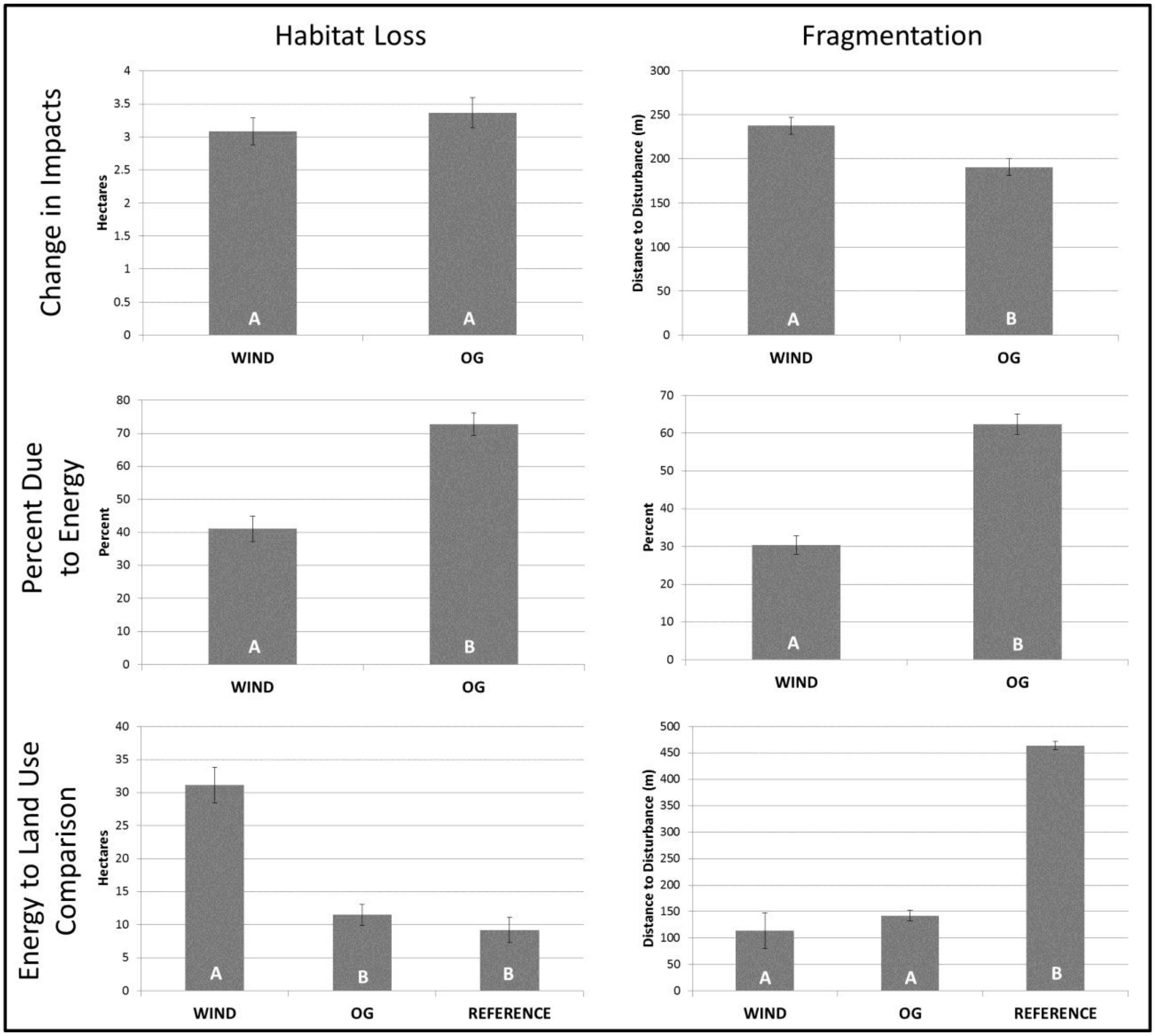

Figure 8. Results of the comparative analysis of impacts of energy development on two indicators (habitat loss and fragmentation).Results are presented as the change in impacts (top), percent due to energy (middle) and a comparison of the three strata (bottom). Different letters represent statistically significant differences ($p<0.05$) and error bars reflect standard errors. The y-axis on the upper and lower fragmentation graphs are distance to disturbance, therefore shorter bars represent higher levels of fragmentation.

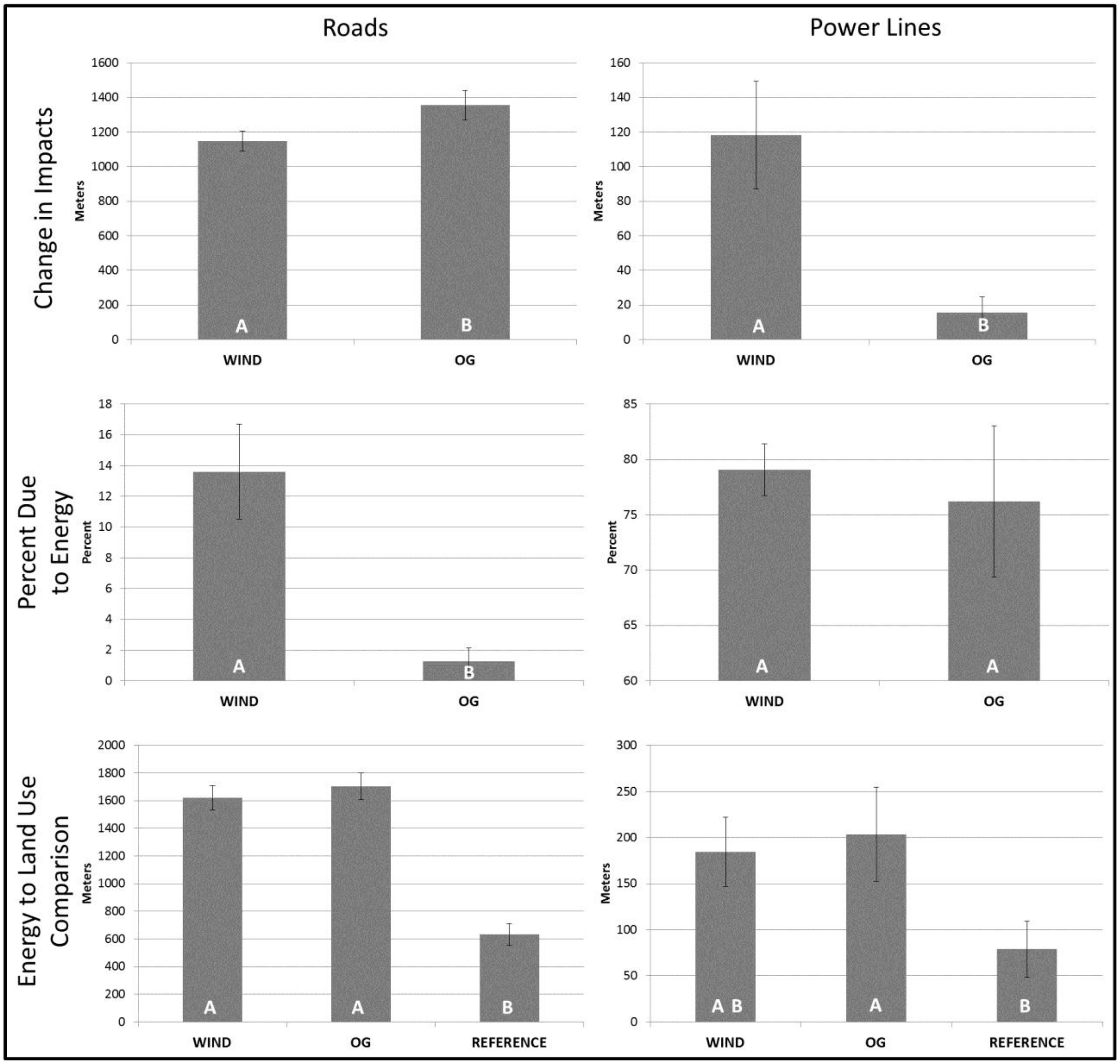

Figure 9. Results of the comparative analysis of the impacts of energy development on the average length of power lines and roads presented as the change in impacts (top), percent of total due to energy (middle) and a comparison of the three strata (bottom). Different letters represent statistically significant differences ($p<0.05$) and error bars reflect standard errors.

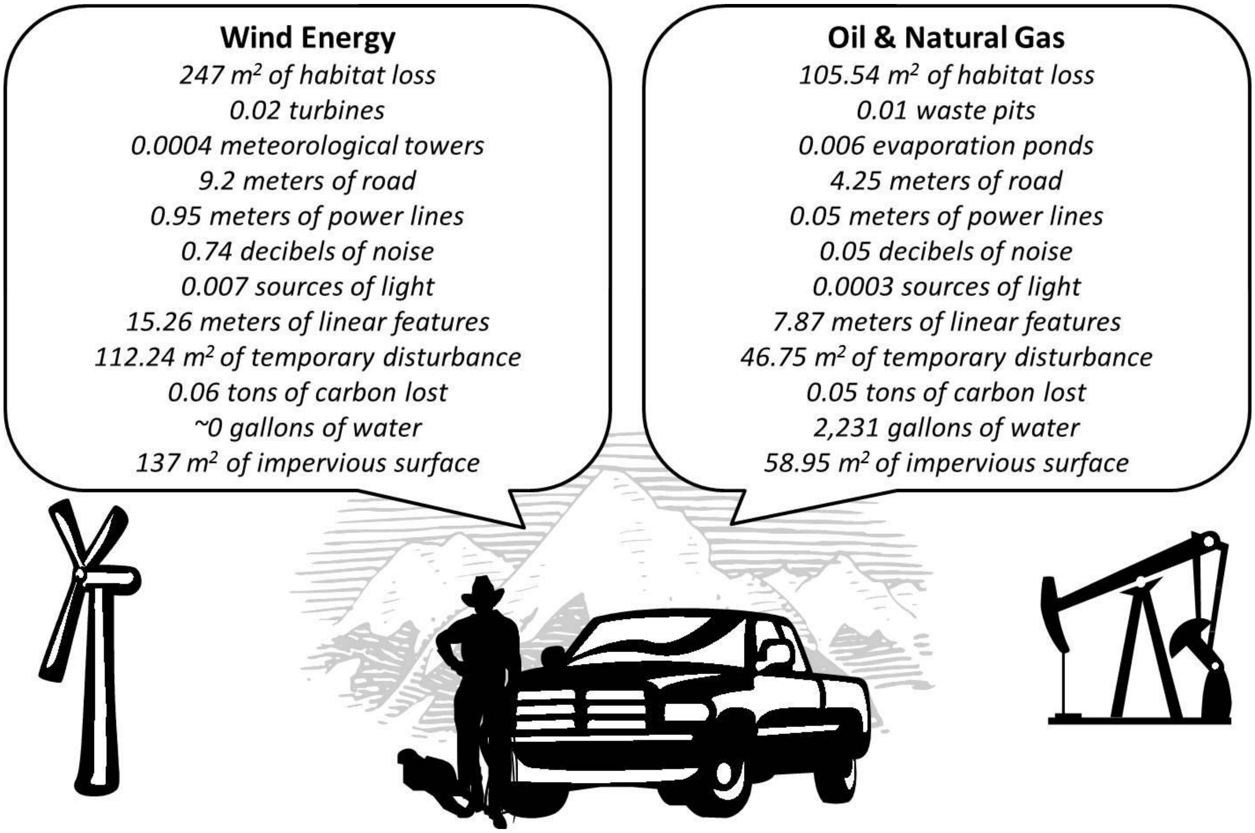

Figure 10. Impacts to various indicators of biodiversity and ecosystem services associated with the average annual energy consumption of a U.S. citizen, with wind energy on the left and oil and natural gas on the right.

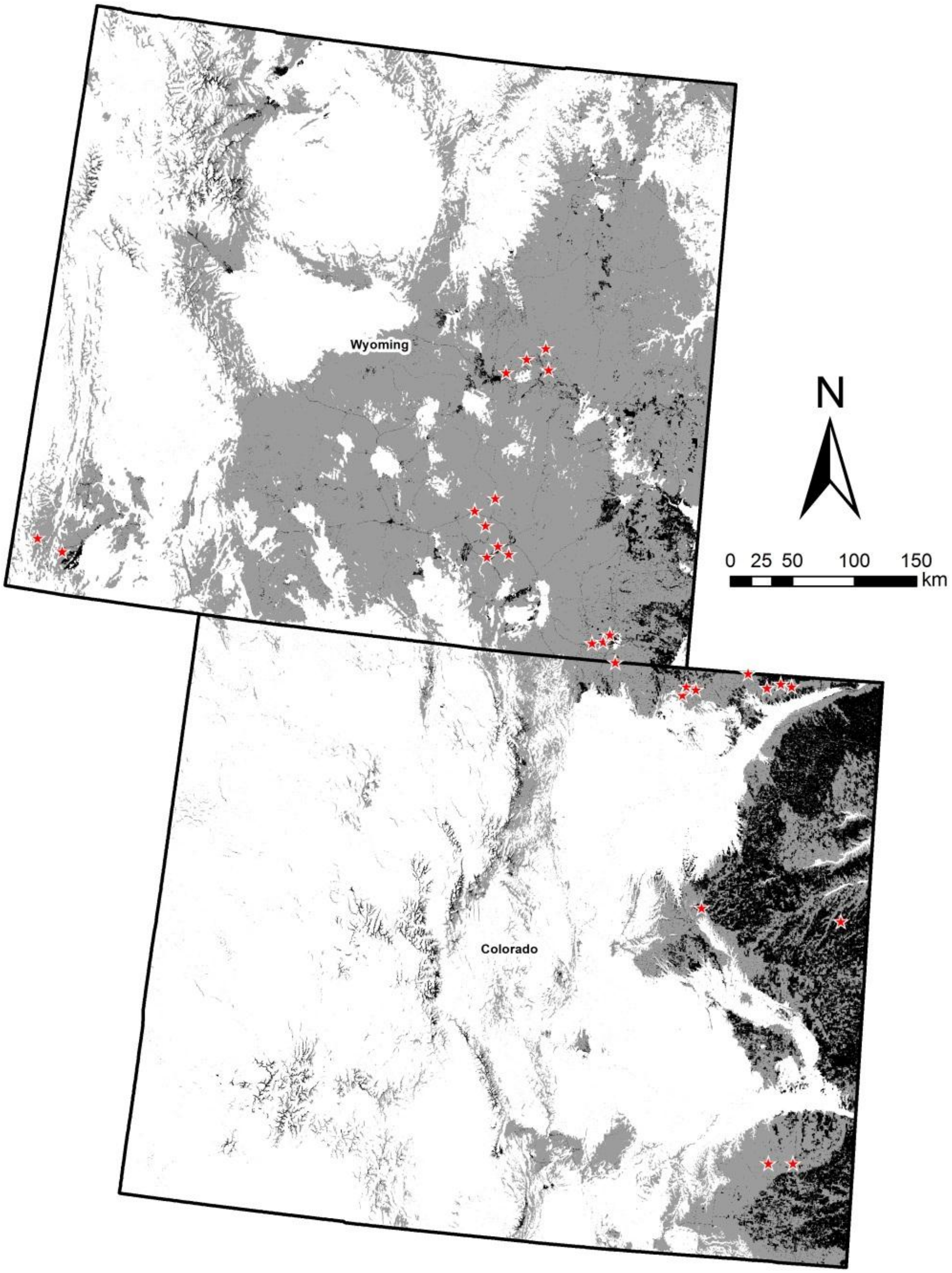

Figure 11. Portions of the study area where wind energy development could occur on previously disturbed lands. Areas where economically viable wind resources as defined by the National Renewable Energy Laboratory (NREL 2003a, 2003b) and previously disturbed lands as denoted by the NLCD (Fry et al. 2011) overlap are shaded black, areas lacking economically viable wind resources are white, and areas of natural or undisturbed lands are shown in grey. Existing wind energy facilities (O'Donnell & Francher 2010; Carr et al. 2011) are denoted by red stars.

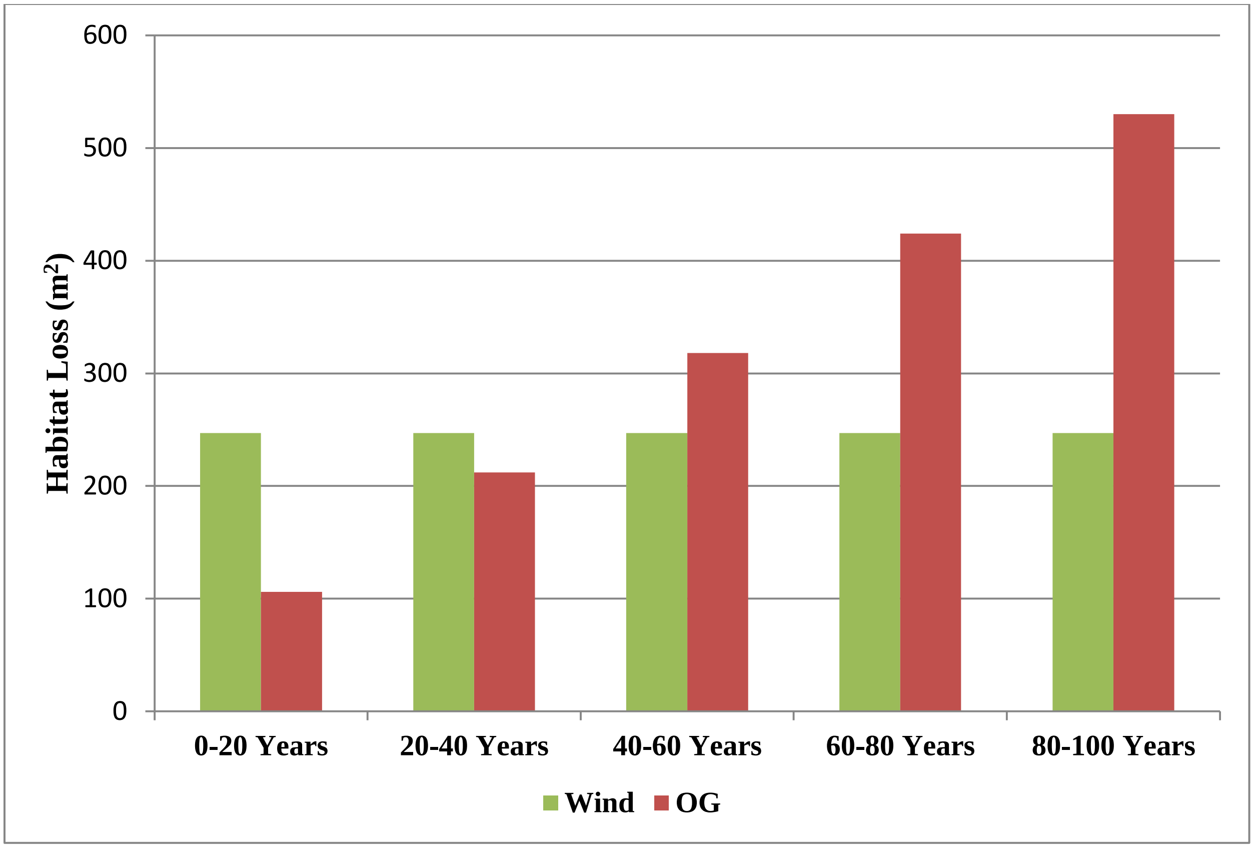

Figure 12. Predicted habitat loss per unit energy produced from wind and oil and natural gas development over the course of 100 years. This analysis assumes that attempts to restore degraded land are unsuccessful and impacts to the flora and fauna communities as a result of energy development are permanent. Energy production and impact estimates are based on a 20 year reported life-span of a normal oil or natural gas well and a modern industrial scale wind turbine (Martinez et al. 2009; EnCana 2011).

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