

# Energy Development in Colorado's Pawnee National Grasslands: Mapping and Measuring the Disturbance Footprint of Renewables and Non-Renewables

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**Abstract** This paper examines the pattern and extent of energy development in steppe landscapes of northeast Colorado, United States. We compare the landscape disturbance created by oil and gas production to that of wind energy inside the Pawnee National Grasslands eastern side. This high-steppe landscape consists of a mosaic of federal, state, and private lands where dominant economic activities include ranching, agriculture, tourism, oil and gas extraction, and wind energy generation. Utilizing field surveys, remote sensing data and geographic information systems techniques, we quantify and map the footprint of energy development at the landscape level. Findings suggest that while oil and gas and wind energy development have resulted in a relatively small amount of habitat loss within the study area, the footprint stretches across the entire zone, fragmenting this mostly grassland habitat. Furthermore, a third feature of this landscape, the non-energy transportation network, was also found to have a significant impact. Combined, these three features fragment the entire Pawnee National Grasslands eastern side, leaving very few large intact core, or roadless areas. The primary objective of

this ongoing work is to create a series of quantifiable and replicable surface disturbance indicators linked to energy production in semi-arid grassland environments. Based on these, and future results, we aim to work with industry and regulators to shape energy policy as it relates to environmental performance, with the aim of reducing the footprint and thus increasing the sustainability of these extractive activities.

**Keywords** Oil and gas · Wind · Energy landscape footprint · Grasslands · Landscape disturbance

## Introduction

Large-scale energy development has extended beyond traditional hydrocarbon sources such as coal, oil and gas (O&G), to include solar, wind, geothermal, tidal, wave, and biofuels. The latter renewable energy sources have become more prevalent in recent years due to technological advancements, cost improvements, environmental concerns, commitments to increased adoption of these technologies, and government subsidies (Durkay 2016; Yu et al. 2016; Heshmati et al. 2015). By 2030 the US aims to increase the global renewable energy share to 30% (IRENA 2014; DOE 2014) and have 20% of its electricity generated by wind (DOE 2008; McNew et al. 2014). Some states, such as Washington, are considering a larger mix of up to 85% for all energy production also by 2030, and 100% by 2050 (Jacobson et al. 2016). In the US, renewable energy is a \$36 billion market (Durkay 2016) and the recent (Apr. 2016) US Senate passage of the energy bill<sup>1</sup> (H.R.8) supports continued renewable and alternative energy

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<sup>1</sup> The official name is H.R. 8- North American Energy Security and Infrastructure Act of 2015 (114th Congress 2016).

resource development (Snow 2016; The Hill 2016; Murkowski 2016; 114th Congress).

Simultaneously, O&G prices have dropped to some of their lowest amounts in 7 years as production has risen to record levels. Technological breakthroughs such as hydraulic fracturing (fracking) and horizontal drilling have created oversupplies in the US (Zuckerman 2014; Lukawski et al. 2014; Milligan et al. 2014), where oil production peaked in March 2015 at nearly 10 million barrels per day (EIA 2016a). Within a year, the price of West Texas Intermediate Crude (the benchmark for US crude oil pricing) fell to a low of \$29.05 USD and conventional retail gasoline prices reached their lowest US national average (in the last 15 years) of \$1.64 USD/gallon (0.44 cents USD/liter) (EIA 2016b, c). From an environmental perspective, an important outcome of low O&G prices and abundant supplies is a less urgent push to adopt renewable energy sources on a large scale. This inaction, nevertheless, contrasts with recent global climate treaties aimed at reducing CO<sub>2</sub> emissions, which necessitate a reduction in hydrocarbon energy sources in favor of renewable ones (Marimuthu and Kirubakaran 2013; McDonald et al. 2009; Yoshioka et al. 2005). Furthermore, because of low prices, drilling has slowed down or even stopped, thus reducing or slowing the O&G footprint in some areas—though as prices begin to climb, this is beginning to change.

In addition to reducing carbon emissions, a key concept behind adopting renewable energy generating technologies is that they are good for the environment; good for the landscape. However, these energy sources create other environmental disturbances through changes in land use and land cover. These include: road and site construction, aerial impacts to wildlife (e.g., birds and bats), as well as habitat loss and fragmentation that may ultimately affect habitat quality and the potential for less biomass storage of CO<sub>2</sub> (Winder et al. 2015; McNew et al. 2014; Jones and Pejchar 2013; Ahmed et al. 2013; Kiesecker et al. 2011; McDonald et al. 2009; Ferguson 2008; Kunz et al. 2007; Leddy et al. 1999).

Thus, renewable energy production can share some of the same impacts that result from hydrocarbon production. The growing research field of “landscapes of extraction” details many of these effects, which include road, noise, and infrastructure disturbance affecting landscapes and wildlife; habitat loss and fragmentation; visual pollution from energy infrastructure (day and night); increased traffic and associated dust; altered waterway drainage patterns; as well as wind-born and water-born soil erosion resulting from new access roads (Winder et al. 2015; Shannon et al. 2015; Finer et al. 2015, 2013, 2008; Wilderness Society 2015; Venier et al. 2014; Mjachina et al. 2013; Mjachina and Chibilyev 2015; Milligan et al. 2014; Baynard et al. 2013; Jones and Pejchar 2013; Baynard 2011; Ledec et al. 2011; Wilbert et al. 2008; Joly et al. 2006; Weller et al. 2002).

Variations in these disturbances can also depend on the age of the projects, distance to water bodies and topographic characteristics. Across the globe in the Russian steppes near Orenburg, we have observed how the northern, older fields exhibited the highest O&G disturbance due to lack of maintenance, the age of the infrastructure and the implementation of older technologies (Mjachina et al. 2013; Mjachina and Chibilyev 2015). There, site suitability factors of O&G projects such as slope, aspect, distance to water sources as well as water samples of nearby streams and rivers are important factors for determining potential hydrologic pollution.

The work reported here is part of an ongoing funded project<sup>2</sup> to quantify and map the energy landscape footprint (ELF) in northeastern Colorado and derive disturbance indicators related to renewable and hydrocarbon energy production in semi-arid steppe landscapes of the western US and southwestern Russia. This particular paper focuses on creating and measuring the ELF, in order for industry and regulators to better plan expansion and future projects while reducing their footprint. While these methods can be used to identify natural (wildness) areas that remain, the reader is pointed to work by others who focus more on land use policy and planning as related to identifying, maintaining and protecting wild places (Larkin and Beier 2014; Van der Berg and Koole 2006; Lupp et al. 2013; Müller et al. 2015; Carver et al. 2013).

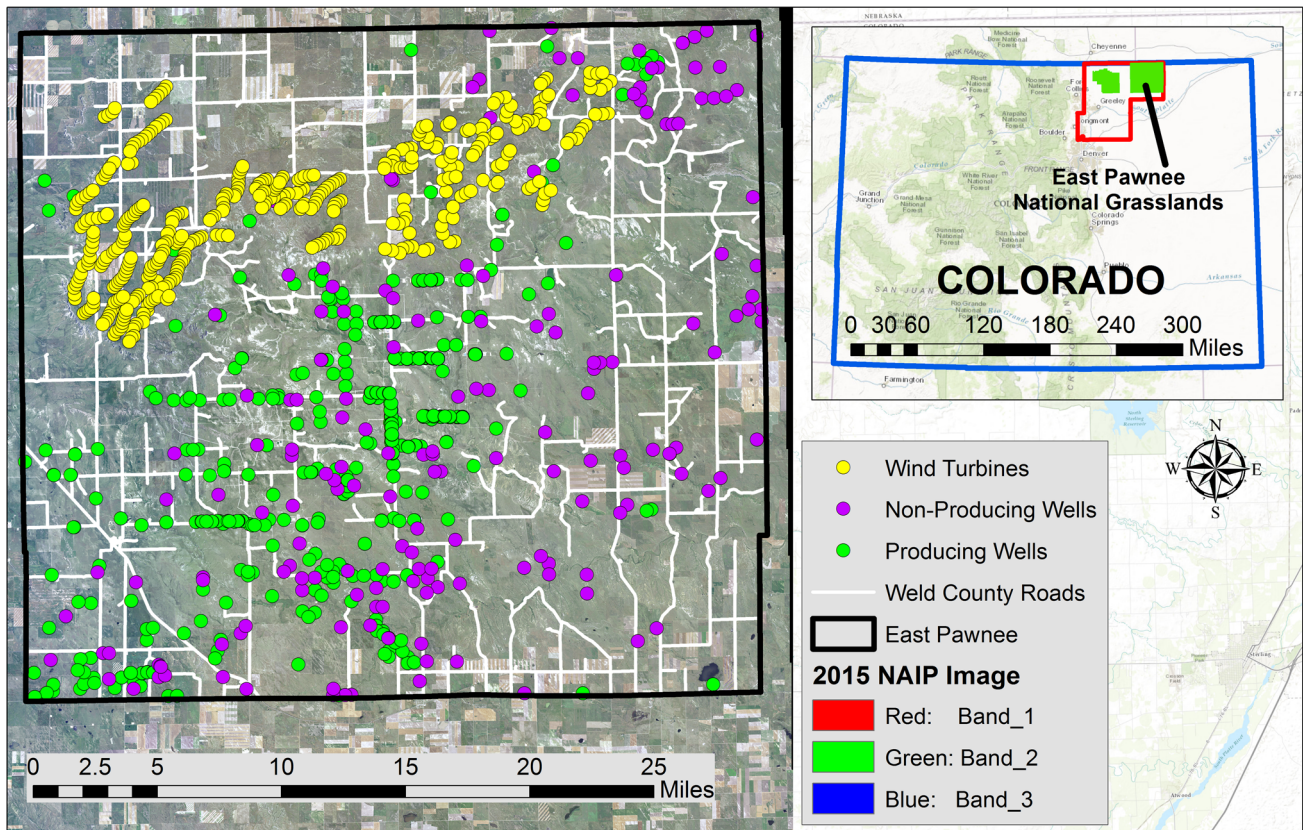
## Study Area

For this study we selected an area (see Fig. 1) of northeastern Colorado, called Weld County, because the landscape is comparable to Orenburg, Russia (our other study site) and because of its prolific O&G and W-E activity. Weld County has the highest oil well density in Colorado<sup>3</sup> (COGCC 2016a) and also contains the Pawnee National Grasslands (PNG). The U.S. Forest Service manages national grasslands for grazing and a variety of other uses including energy production. The mix of federal, state, and private lands within the PNG boundary contains competing economic interests that include agriculture, ranching, O&G extraction, and W-E production. Because the eastern side of PNG is larger, has much more O&G production and harvests W-E (Cedar Creek I and II wind farms), we selected this part as our study area (see Fig. 1) referred to hereafter as Pawnee National Grasslands eastern side (PNGE).

Figure 2 shows the location and size of the PNGE administrative boundary along with the amount of federally

<sup>2</sup> CRDF Award Number: OISEJ14J61033J0, Analyzing the geo-ecological state of steppe ecosystems affected by oil and gas production in North Eurasia and North America.

<sup>3</sup> Colorado is the 7<sup>th</sup> largest oil-producing US state in 2016 (EIA 2016d) and was the 6<sup>th</sup> largest gas producer in 2014 (EIA 2016e).



**Fig. 1** Study area and the location of O&G and W-E features

owned and managed National Grassland Units, oil fields and leases. The amount of federal land (National Grassland Units) is about 382 km<sup>2</sup>, or 18% of the East Pawnee study area.

**Pawnee National Grasslands**

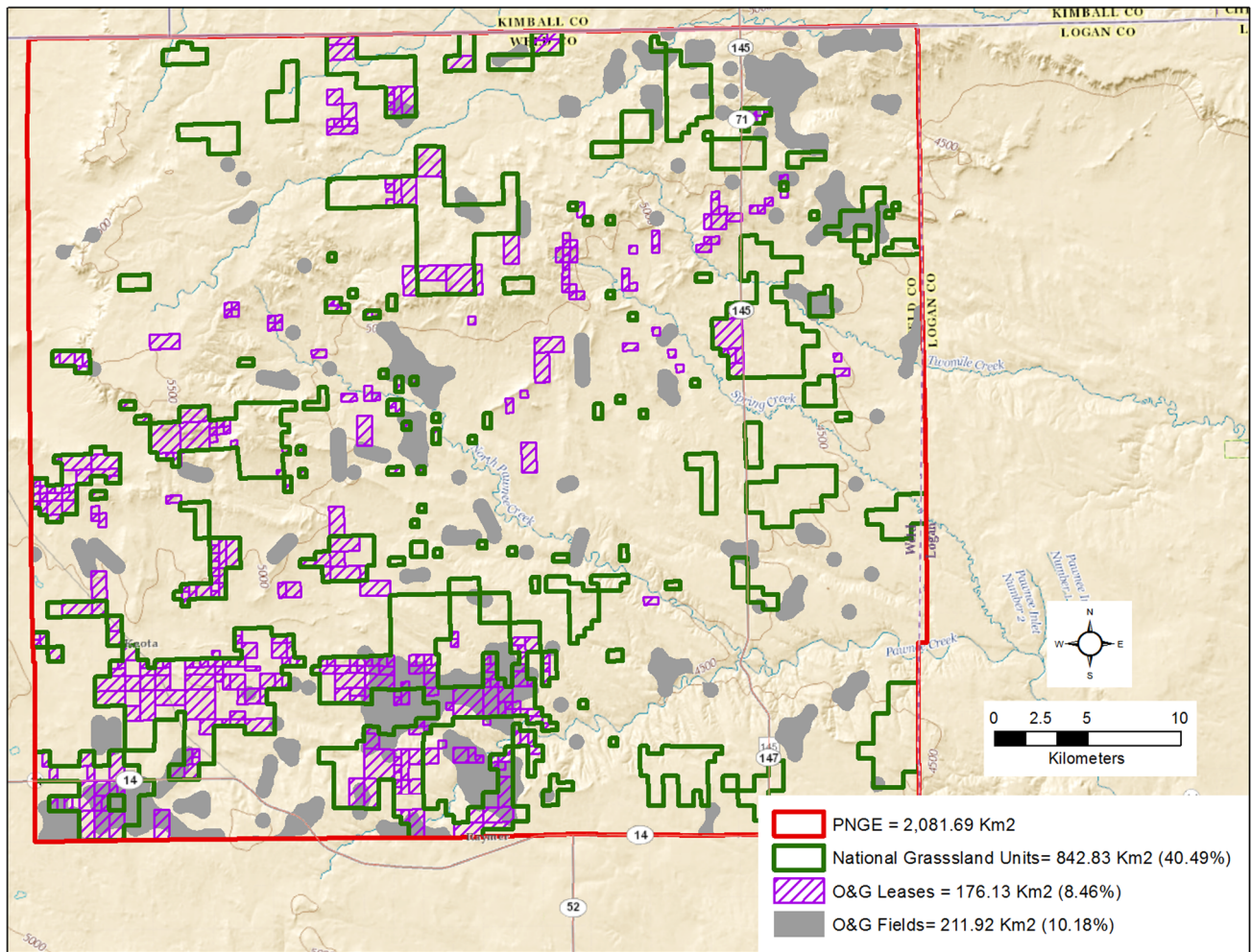
The PNG are located within a semi-arid steppe zone characterized by few areas of water, dry winds for much of the year and the prevalence of grassy vegetation cover that has been around for at least the last 20,000 years (Chibilyev 2013; Lane and Nichols 1999; Duram 1995). They comprise 3106.45 km<sup>2</sup> of land located in northeastern Colorado. Managed by the US Forest Service, they form part of the Great Plains grasslands, the most endangered ecosystems in North America (Preston and Kim 2016; WCS 2011).

Not all of this land is federally owned however. Current tenure patterns trace to the legacy of populating the US West, which informally began with California’s gold discovery in 1848 (Duram 1995). Determined that the area should be settled (with non-Native Americans), Congress designated the Colorado Territory in 1861 and passed the Homestead Act of 1862, providing 65 ha and later increased to 130 ha to each homesteader who would farm the land and establish a home (Milligan et al. 2014; 43 U.S.C section 161

1862, repealed). Importantly, “These acts/laws were aimed primarily at land east of and along the west bank of the Mississippi River and were not appropriate for the high plains” (Rhoads and Rhoads 2013). Nevertheless, by the early 20th century more than 500,000 farms and 404,685 km<sup>2</sup> had been claimed by homesteaders. Unfortunately, many of the settlers discovered that low rainfall, droughts, floods, insect invasions, and erosion made the land unusable for most farming endeavors (Olson 1997); particularly evident during the Dust Bowl of the 1930s (Rhoads and Rhoads 2013). In fact, “nearly all the Great Plains receives less than 610 mm of rainfall a year, and most of it receives less than 406 mm” (Trimble 1980: 2).

Realizing its error, the government launched the “land utilization program” by re-purchasing large tracts of the Great Plains from the settlers and attempted to make the best use of this land (Rhoads and Rhoads 2013; USDA 1965). This was followed by the Bankhead–Jones Farm Tenant Act which tried to develop a program of conservation and land utilization (Bankhead–Jones Tenant Act 1937). By 1960 the Secretary of Agriculture designated the purchased areas of the Great Plains as national grasslands<sup>4</sup>.

<sup>4</sup> Twenty National Grasslands exist in the US today, located in 12 states and totaling 15,550 km<sup>2</sup> (Olson 1997).



**Fig. 2** PNGE study area showing the location of federal lands (national grassland units) O&G leases and O&G fields

The Secretary was granted broad powers to control erosion, preserve natural resources, protect fish and wildlife, develop energy resources, and conserve subsurface moisture. This power included permitting of grazing on the grasslands (7 USC Section 1281 1981). Today, “Grazing cattle, remnant homesteads, and barbed-wire fences are accepted components of the Grassland’s landscape character” (Milligan et al. 2014: 2017).

Soils also limit agricultural production, with the mixture of clays, calcium carbonate silica, salts, and gypsum resulting in highly erodible soil (Milligan et al. 2014) that is usually unproductive for farming as evidenced by the failed attempts of the government to populate the area with farmers in the last century. Grasses, shrubs, and succulents make up the majority of the vegetation in this short grass prairie ecosystem, with the chief native plant populations being blue grama (*Boutelova gracilis*) and buffalo grass (*Boutelova dactyloides*) (Milligan et al. 2014; Hazlett 1998). While the wettest months are May through August, available moisture is the most limiting factor on vegetation

growth (Milligan et al. 2014; Hazlett 1998). NOAA (2017) records indicate that average yearly precipitation for the PNG is 426 mm, with the highest amounts occurring May through August. And as Olendorff (1972) observes: “these early settlers learned by experience that the nonirrigable land of northeastern Colorado was suitable for only two forms of agriculture, namely cattle ranching and dryland grain production.”

Today, land use is an eclectic mix of windmills, nuclear tipped multi-warhead missiles, herds of cattle, and oil and natural gas wells (our own fieldwork 2015, 2016; Janke 2010; USDA FS 2016a). Windmills generate enough electricity to power 165,000 homes (Power-Technology 2015a; 2015b), while nuclear missiles hide beneath the surface (Power-Technology 2015a; 2015b; Kelly 2014; Thirdtable 2013; Roso and Dukes 1988). At least 12 underground Minuteman missile sites are located in the PNG, part of a force estimated at 150 spread across the plains (NTLLCS 2014; Rhoads and Rhoads 2013). Over 8500 cattle graze on the Pawnee typically for 5-month periods (NTLLCS 2014).

If the rainfall is abnormally light, the period is reduced in an attempt to protect the lands from permanent damage.

Oil wells (traditional and fracking) are also found throughout the grasslands and the Bureau of Land Management (BLM) manages mineral rights. While drilling may seem inconsistent with conservation, the US Forest Service mandate includes natural resource development known as “multiple use sustained-yield.” As mentioned earlier, control over the grassland consists of a patchwork of federal, state, local, and private land ownership. However, jurisdiction of *mineral rights* exemplifies the challenges of the grasslands. Almost 1/3 is controlled privately, another 1/3 having mixed federal and private rights and the approximately 40% remaining is administered by the BLM.

While restrictions on O&G drilling are in place for some 1215 ha and another 5666 ha are under a “no surface development” ban, the bulk of the grasslands (90%) are open to O&G extraction (NTLLCS 2014). Furthermore, as of February 2015, any future O&G development on federal lands must be done as a no surface disturbance (USDA FS 2015), meaning that drill rigs and tanks cannot be brought onto these grassland (Jaffe 2015) but horizontal drilling can be used on private lands to access leased deposits underneath federal lands (Milligan et al. 2014).

Regarding wind energy (W-E), the 397 wind turbines examined in this study were part of a 2-phase construction project, Cedar Creek I and II. The former was commissioned in 2007, contains 274 turbines and has an output of 300 MW (USGS 2015; Power-Technology 2015a). Cedar Creek II, located further east, was commissioned in 2011, contains 123 turbines and has an output of 250 MW (USGS 2015; Power-Technology 2015a, b). Both projects are located in the northern half of PNGE. Persistent winds normally blow southwest to northeast or northwest to southeast and often blast over 48 km/hr (Milligan et al. 2014).

Combined, the energy produced can power 165,000 homes, which provides a surplus of electrical energy, given the small population in this area—though this energy is destined for other markets. None of these turbines are located on federal lands (national grassland units). However, bird watching is one of the main tourist attractions to the PNG (attracting more than 3000 tourists per year—Milligan et al. 2014), and avian wildlife adversely affected by W-E include golden eagles as well as bats (Philbrook 2015, personal communication; Stage 2017 personal communication).

As a local social issue, the electricity generated here does not serve nearby communities even while the local roads experience wear and tear from maintenance vehicles headed to wind turbines. This upsets nearby residents such as those in the town of Grover, about 7 km away from the nearest turbines (Counts 2016, personal communication). The same

complaints have been expressed by local residents regarding O&G trucks plying local roads (Stage 2015, personal communication; Koppang and Dunn 2014).

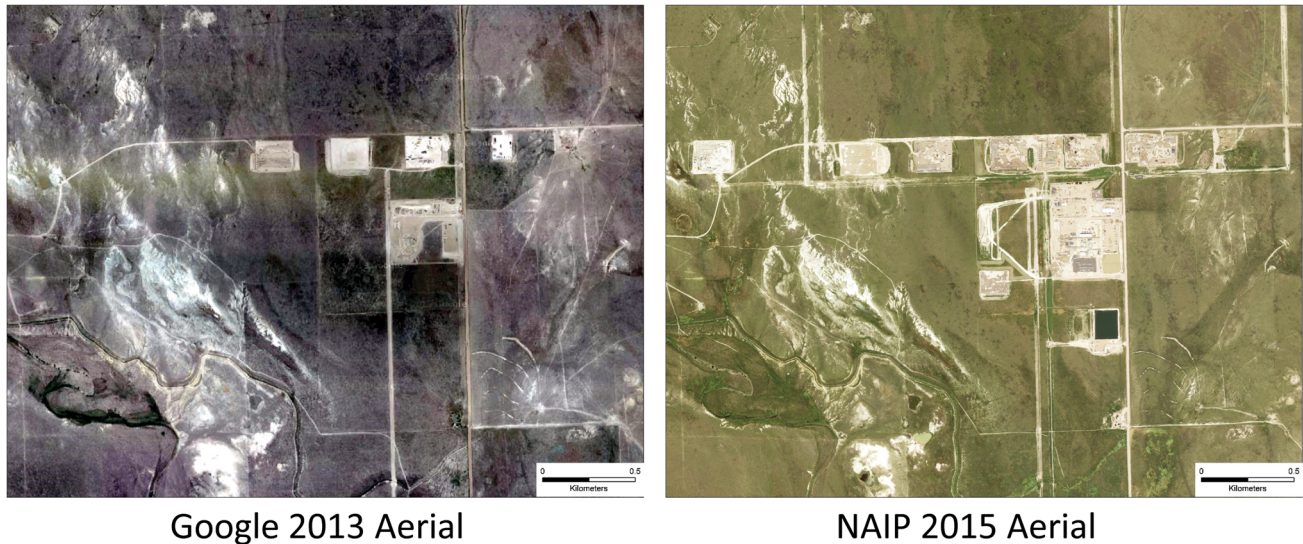
## Materials and Methods

Geographic information systems (GIS) analysis was accomplished using ESRI's ArcGIS 10.4.1 (ESRI 2016) and datasets were projected to NAD 1983 UTM zone 13 N. We selected a 2015 National Agricultural Imagery Program (NAIP) 1-meter resolution aerial image of Weld County (NAIP 2016) because it coincided with our same-year fieldwork data. Though Google Earth's imagery often had a higher spatial resolution in the PNGE, temporally it dated to 2013 and a lot of changes occurred in 2 years (see Fig. 3). Similarly, ESRI's image service had pockets of higher resolution that varied according to the map scale. Thus, we relied on NAIP imagery (whose 1-m resolution proves effective for identifying and digitizing infrastructure features).

To delimit the PNGE, we utilized a GIS shapefile of the US National Forest Service boundaries in Colorado (USDA FS 2016b) and extracted the PNGE study area (USDA FS 2016b). We then selected the land parcels located here and calculated the amount and percent of land owned by each of the entities provided in the database (Weld County GIS). Based on Colorado Oil and Gas Conservation Commission's oil well spatial data, 2478 wells were located in the study area, however, only 561 were producing wells, and we extracted those. Next, we created a 1 km<sup>2</sup> grid for the 2081.69 km<sup>2</sup> PNGE and systematically examined each cell to pinpoint these wells (COGCC 2016a) and ensure they were discernible in the landscape. After all, we too found that “well locations are not always accurate” (Preston and Kim 2016: 1513).

Through this approach we identified 444 wellpads of varying size and digitized each one, creating direct disturbance polygon areas. Direct disturbance refers to the amount of land physically occupied or disturbed by the presence of infrastructure features (also termed habitat loss). Wellpads are the large, open, flat, and stable rectangular areas created to install the wells and supporting equipment such as storage tanks, waste pits, compressors, flares, and machinery (CSUR 2015).

Next, we identified and digitized the 444 access roads leading to each of the wellpads (following methods utilized by Baynard et al. 2013) and measured the specific width of each road according to the NAIP imagery. Then we buffered these linear access roads to their specific width to create a polygon area file. Finally, we merged and dissolved the buffered access roads and wellpads to create an O&G



**Fig. 3** Comparison of Google Earth imagery (2013) to the NAIP (2015) imagery used in our study

disturbance footprint for each wellpad/access road (see Fig. 4a and b).

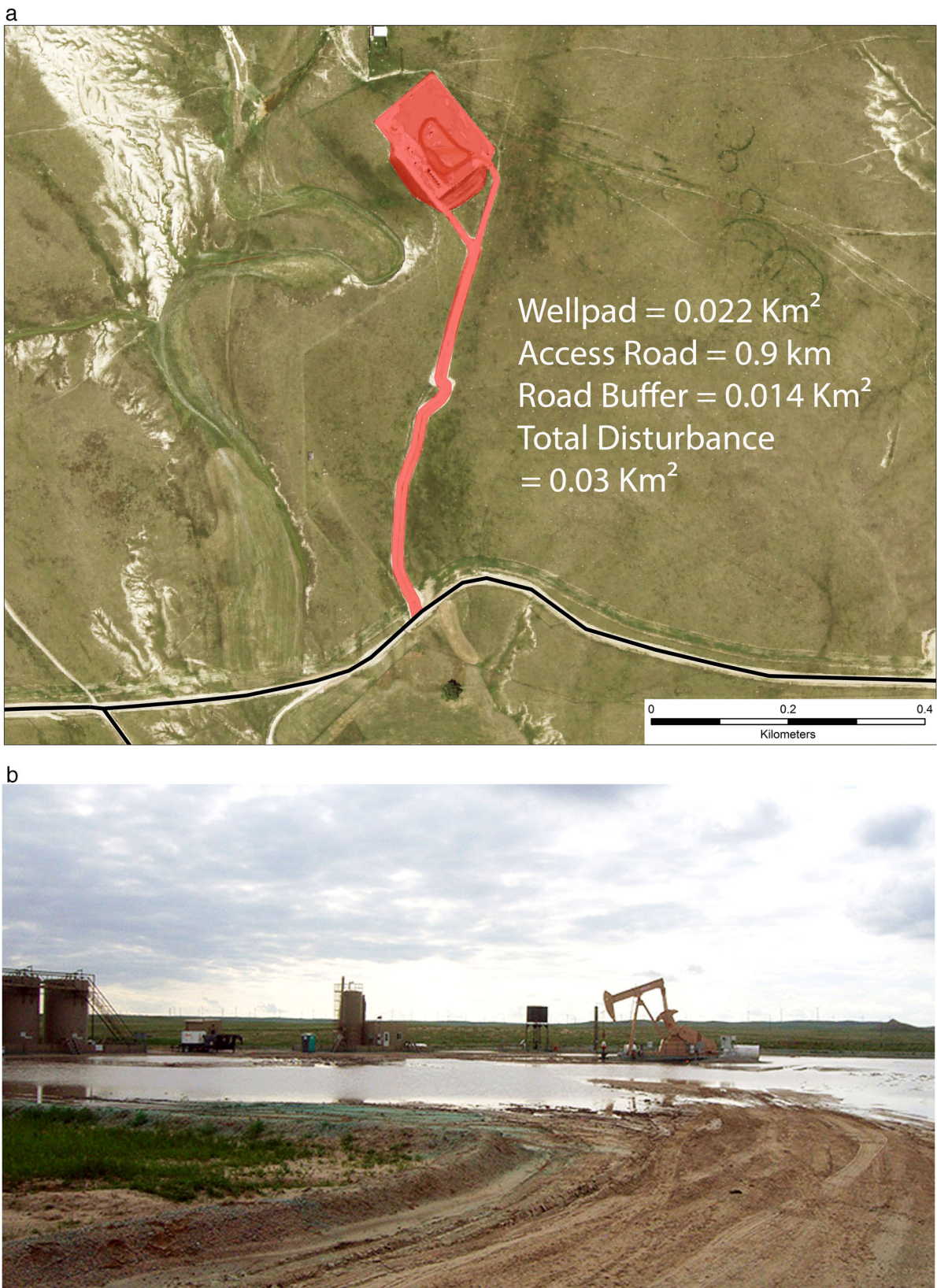
While producing O&G wells were the dominant hydrocarbon-based surface disturbance, older, abandoned, plugged, or legacy wells were also evident in the landscape. In order to account for the disturbance created by these wells, we examined 1917 non-producing wells in the study area. Using the NAIP (2015) imagery, we overlaid the 1 km<sup>2</sup> fishnet and selected those blocks containing these “other” wells. Then, one-by-one, we visually analyzed the 879 selected blocks to determine if wellpad disturbances were evident in the landscape. As we examined the nearly 2000 wells, we deleted those that were no longer discernible in the landscape. Sometimes six or more wells appeared in one location (former wellpad) with no evident disturbance, so the number of deleted wells decreased significantly. Meanwhile, we also added 94 well locations that were visible and not part of the “producing wells” dataset, resulting in 435 wells. Finally, to ensure that we were not over counting wells, we checked to see if any non-producing wells were indeed located inside our already digitized O&G footprint and removed them.

In many cases, these non-producing wells showed a disturbance in various stages of recuperation and quite often the access roads were hard to perceive. This time, rather than digitizing each of these non-producing wells (and access roads), we applied the disturbance value of 0.028 km<sup>2</sup>. This figure was derived from the average direct disturbance footprint size of a producing well and access road—which we digitized for the entire study areas. Calculating the radius of a (buffered) circle: 0.0944 km<sup>2</sup>, or 99.40 m, we used this figure to buffer the 185 non-producing wells and generate a non-producing footprint.

For the wind landscape we followed similar methods to create the wind turbine footprint. First we had to find and digitize all 397 wind turbines of the Cedar Creek I and II wind projects<sup>5</sup> (Pacific Power 2016). We digitized each turbine center point to the location where the turbine tower met the ground in the NAIP imagery. During this process we noted that most turbine pads had a uniform (rounded) size so we randomly selected 20 turbine points (using Microsoft Excel’s random number generator (Microsoft 2016)), measured the disturbance length and width of the pad area and calculated an average turbine pad size of 75.825 m<sup>2</sup> (see Fig. 5a and b). Assigning this figure to all pads, we buffered them to produce circles representing actual pad disturbance, and visually examined them to confirm they properly represented average turbine pads.

Next, we digitized other W-E infrastructures including access roads, transmission lines, substations, and discernable easements housing underground cable lines. The latter appeared as linear ground disturbances in various stages of recuperation and we digitized those that were detectable. Given that they are part of the W-E footprint, we included them in the calculations. However, over time as they disappear and natural vegetation returns, they may no longer be included. We buffered the access roads, transmission lines and easements to their standard width as evidenced in the NAIP imagery to create area disturbance.

<sup>5</sup> After digitizing wind turbines and initial analysis was completed, we found a USGS dataset containing these and other onshore wind turbines in the US updated to March 2014. So while our dataset was updated to February 2016, we used some the attribute information provided in the USGS set (USGS 2015).



**Fig. 4** **a** The O&G footprint for a given wellpad and access road in our study region, including disturbance values. **b** Wellpad disturbance as evidenced in the field, June 2015. *Note:* much of the wellpad is inundated (due to unseasonably high rainfall amounts in spring 2015)



**Fig. 5** **a** The W-E footprint for a given turbine pad and access road in our study region, including disturbance values. **b** Turbine disturbance footprint as evidenced in the field, June 2015



Because the wind turbines are visible from quite a distance due to their height, we used the viewshed analysis tool in ArcMap (ESRI 2016) to identify the locations in the study area where wind turbines would be visible. To accomplish this we obtained two digital elevation models (DEMs) from the USDA (USDA FS 2016a, b) with 30 m spatial resolution and mosaicked them (using ArcMap 10.4.1). We then clipped them to our study area and utilized the viewshed tool in ArcMap, resulting in a two-color model showing areas where wind turbines were visible or not.

Notably, not all roads present in the landscape were built for energy development, so we integrated transportation roads located in the PNGE using data provided by Weld County (Weld County GIS 2015). Based on values from the Colorado Department of Transportation (CDOT 2011), these roads were buffered a uniform distance (11.42 m) to estimate direct effects of the non-energy roads on the landscape.

Finally, a closing calculation was needed to truly understand infrastructure disturbance in PNGE. These were core or roadless areas that remained once all infrastructure disturbance features were identified and a *setback distance* buffer added to account for road edge effects (distance at which ecological effects extend out from infrastructure features (Forman et al. 2003)).

Following findings by Pruetz et al. (2009) regarding W-E development in the US Great Plains prairies, O&G edge effects disturbance on natural vegetation (WCS 2011), and road-effect zone on large mammal population densities (Forman and Alexander 1998) we buffered direct disturbance footprints of O&G, wind, and transportation by 100 m. We acknowledge that there is insufficient information to determine a clear edge effect zone in this steppe environment and more research is indeed required. Our choice of this distance was to account for fences, which are abundant in PNGE, and which provide barriers to cattle movement and possibly to large wildlife (though we did observe pronghorn (*Antilocapra americana*) jump over and through barbed wire fences). As Preston and Kim (2016: 1512) observe: “the effects of energy development on biodiversity and ecosystem services are poorly understood.”

An additional consideration on the choice of the extended buffer (edge effect) is the current Colorado regulatory setback distance of 152.4 m (500 feet) required between O&G development facilities and buildings such as homes (COGCC 2016b).

Considering that some overlap occurred when combining road segment datasets (i.e., oil access roads and transportation roads), we merged and dissolved all infrastructure features (using ESRI's ArcMap) to generate a footprint of extended disturbance. We then extracted the extended footprint from the PNGE to yield core roadless areas. After removing slivers (minute patches in the polygon spatial data

set) and other small polygons under 0.5 km<sup>2</sup>, 148 patches remained, ranging in size from 0.5 to 170 km<sup>2</sup>.

Next, we acquired a 2015 land use land cover (LULC) data set in raster format of Weld County, Colorado from the US National Agriculture Statistical Service (NASS 2016). We converted this raster-format data into a shapefile for the PNGE and recoded the 28 land categories into 6, following methods by Baynard et al. (2014). Following these methods, the 16 agricultural categories (such as barley, corn, and sunflowers) were classified as agriculture, and the remaining classes were combined using existing names (for example deciduous and evergreen forest became simply forest). The ensuing six categories were:

- Agriculture
- Barren/Shrubland
- Developed
- Forest
- Grass/Pasture
- Open Water/Wetlands

Using this recoded LULC data, we calculated the amount of land and the percentage of the total study area dedicated to each category. To get a better sense of what type of LULC category was being affected the most by energy development, we clipped the direct disturbance footprints related to W-E, O&G and transportation from the LULC map and again calculated the amount of land and percentage of area disturbed. Additionally, we looked at national grassland units (federally owned lands inside PNGE), oil fields, the buffered (extended) footprints and the core/roadless areas—see Tables 1a, b–5. The results are described below.

To summarize, digitizing the infrastructure features for O&G and W-E, as well as examining existing data sets allowed us to create the following disturbance metrics in the PNGE—see Tables 1a, b–5:

- Road length (linear km of roads)—for O&G, W-E, and transportation
- Road density (linear km of roads per km<sup>2</sup>)—for O&G, W-E, and transportation
- Number of wells
- Well density (number of wells per study area)
- Number of wellpads
- Wellpad density (number of wellpads per study area)
- O&G footprint (habitat loss area created by the direct disturbance of wellpads and access roads—for producing and non-producing wells)
- Number of wind turbines
- Turbine density (number of turbines per study area)
- Wind easements
- Wind transmission lines
- Wind substations

**Table 1a** Land ownership parcels in the PNGE

Owner	Number of parcels	Number of Owners	Area (km <sup>2</sup> )	Percent of area
USA (Federal Government)	348	1	377.75	18.16
State of Colorado	64	2	119	5.72
Private owners with parcels > 1% of PNGE = 12	309	13	500.08	24.04
Private owners with parcels < 1% of PNGE = 515	1524	514	1084.87	52.08
Total	2245	529	2081.69	100

**Table 1b** Land parcels with wind turbines and oil and gas wells in the PNGE

Activity	Number of parcels	Type and number	Area (km <sup>2</sup> )	Percent of study area
Parcels with oil and gas wells (producing and non-producing)	291	Agricultural (230) Exempt-Federal and State Government (59) Real State Assessed (2)	424.83	20.43
Parcels with wind turbines	98	Agricultural (89) Exempt (8) Real State Assessed (1)	176.11	8.47
TOTAL	389		600.94	28.90

**Table 2a** Oil and gas disturbance values for producing wells

Oil & gas producing footprint	Length (Km)	Density (km/km <sup>2</sup> )	Direct Effects (Km <sup>2</sup> )	% of Area
Producing wells = 561		0.27		
Wellpads = 444			10.54	0.51
Roads	275.49	0.13		
Roads direct effects			2.16	0.10
Total producing footprint			12.63	0.61

**Table 2b** Oil and gas disturbance values for non-producing wells

Oil & gas non producing footprint	Density (km/km <sup>2</sup> )	Direct Effects (Km <sup>2</sup> )	% of Area
Non producing wells = 185	0.09		
Total non producing footprint (based on 0.0281 km <sup>2</sup> /well)		4.87	0.23

**Table 2c** Combined producing and Non-producing Oil and Gas Footprint

Combined oil and gas footprint	Density (km/km <sup>2</sup> )	Direct effects (km <sup>2</sup> )	% of Area
Combined wells = 746	0.36		
Total combined footprint		17.5	0.84

- W-E footprint (habitat loss area created by the direct disturbance of turbine pads, access roads, substations, transmission lines, and easements)
- Transportation footprint (habitat loss area created by the

direct disturbance of transportation roads)

- LULC affected
- Core areas—or roadless zones (land located away from development)

## Results

### Land Ownership

As mentioned in the introduction, the PNGE is comprised of state, federal, and private ownership. Based on Weld County parcels data (Weld County GIS 2016) there are 2245 parcels and 529 land owners, with the federal government being the largest, followed by some large-holding private parties and then the state government (see Table 1a, b). O&G activities are found in about 20% of the parcels, classified primarily as agriculture. Wind turbines are found in about 8% parcels, almost entirely labeled as agricultural.

**Table 3** W-E disturbance values

	Length (Km)	Density (km/km <sup>2</sup> )	Area (Km <sup>2</sup> )	% of Area
Turbines (= 397)		0.19	1.80	0.09
Roads	149.24	0.07		
Roads direct effects			1.42	0.07
Wind easement lines	64.11	0.03		
Wind easement direct effects			0.65	0.03
Transmission lines	86.30	0.04		
Transmission lines direct effects			0.28	0.01
Substations			0.19	0.009
Wind footprint			4.34	0.21

**Table 4** Transportation disturbance values

	Length (km)	Density (km/km <sup>2</sup> )	Direct Effects (km <sup>2</sup> )	% of Area
Roads (km)	1087.86	0.52	12.37	0.59
Transportation footprint			12.37	0.59

**Table 5** Disturbed and core/roadless areas

Buffered disturbance	Km <sup>2</sup>	% of Study Area
Wind buffered zone	31.87	1.53
Oil Buffered zone (Producing)	48.28	2.32
Oil buffered zone (Non-Producing)	11.30	0.54
Transportation buffered zone	119.20	5.73
Combined disturbance buffered zone	210.65	10.12
Overlap	12.98	0.62
True disturbed buffered zone	197.65	9.49
Core areas	1884.04	90.51

## Oil and Gas Disturbance

The O&G footprint stretched out diagonally across the PNGE from southwest to northeast. The northwest and southeast zones were mainly devoid of activity. As mentioned above, the PNGE contained 444 discernable wellpads. The length of oil access roads was 275.49 km. This is comparable to the 299.65 km linear disturbance measured from the wind projects (access roads, easements, and transmission lines). However, the average wellpad by itself (no roads) was 425% larger than the average turbine pad.

In order for the reader to more easily visualize the amount of direct disturbance, or habitat loss created by the presence of these energy features, we converted km<sup>2</sup> into units equivalent to soccer fields (SFs). According to FIFA (Fédération Internationale de Football Association), a regulation soccer field has a maximum area of 8250 m<sup>2</sup>, or 0.00825 km<sup>2</sup> (110 × 75 m—FIFA 2015). In our scenario, the average wellpad disturbance (no roads) was 0.023 km<sup>2</sup>,

or 2.79 SFs. In the PNGE, during initial construction wellpads can measure almost 6 SFs (0.049 km<sup>2</sup>) and after reclamation may be reduced to less than 1 SF (0.006 km<sup>2</sup>). The total O&G footprint created by wellpads and buffered roads equaled 12.63 km<sup>2</sup>. This averages to a disturbance of 0.028 km<sup>2</sup> per wellpad, or 3.39 SFs.

Also, while wells under current production were the focus of our O&G disturbance measures, they were not the only ones located in our study area. We therefore examined the location of all 1917 *non-producing* and determined which ones still exhibited surface disturbance in the imagery. The number of visible well disturbances dropped to number 435. Yet, in order to not *over count*, we identified any that were located inside the already digitized O&G footprint. Over half of the wells, 246, were found here, leaving 185 non-producing wells in our study area whose direct disturbance needed to be calculated.

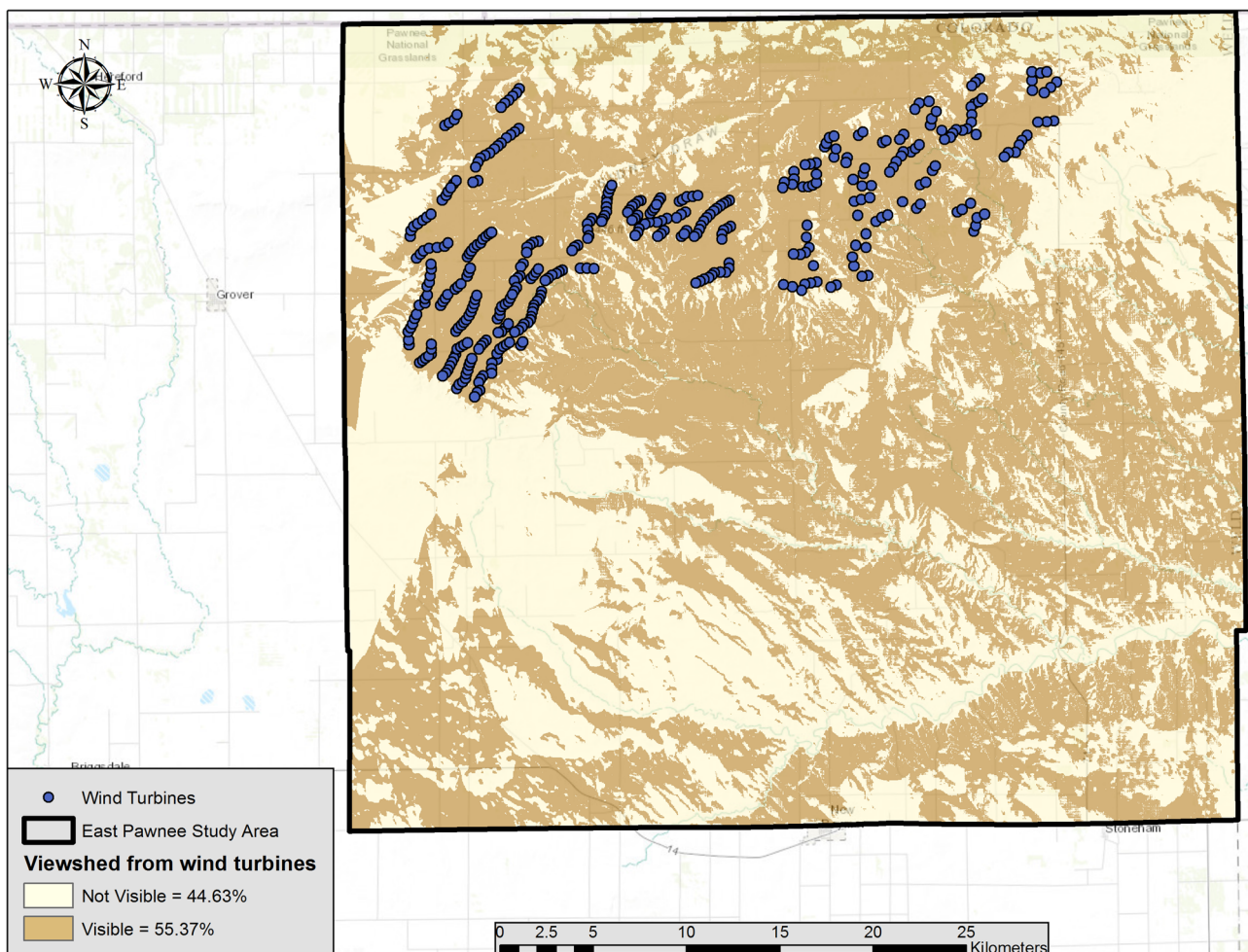
Using the standard value of 0.028 km<sup>2</sup>, which represented the direct disturbance of each wellpad and access road, we solved for the radius, which equaled 0.0944 km<sup>2</sup> (94.4 m). Buffering these wells to that size resulted in a direct disturbance of 4.87 km<sup>2</sup> for non-producing wells. Because multiple wells occurred together in some locations, such as an old well pad, there weren't 185 distinct buffered observations. If so, the calculated disturbance would have been a simple: 185 × 0.028 = 5.18 km<sup>2</sup>. This shows the importance of using spatial data calculations to get a more accurate representation. Combined, the producing and non-producing O&G disturbance resulted in a 17.5 km<sup>2</sup> footprint, which equals 2121 SFs.

Compared to wind, the average O&G footprint was 191% larger than the average turbine pad footprint. Of interest, only 22.42% of the O&G footprint is located in areas designated as oil fields, while 45.79% of the (estimated) non-producing footprint are located in oil fields. The indication that older drilling activity occurred on top of these fields but has shifted outside of them is a topic for further research. Also, only 0.14% of the producing footprint and 0.28% of the non-producing footprint is located in National Grassland Units, confirming parcel data records showing that the great majority of O&G development occurs on private lands, which is also consistent with U.S. National Forest Service information (Milligan et al. 2014). A small amount, 0.40% of the O&G producing and 0.34% of the non-producing footprint, are located inside O&G lease zones. While the location of leases changes over time, it is surprising that current and past oil activities (in 2015) were mainly found outside these locations.

## W-E Disturbance

Stretching almost completely across the boundary—38.5 km, about 80% of the expanse of the PNGE is affected by W-E development. This means that if traveling across northern PNGE, windmills are likely visible in the distance, as they are located on the high ridges. Our viewshed analysis, indicated that the wind turbines were visible in about 55% of the PNGE (see Fig. 6).

The landscape disturbances created by W-E included 149.24 km of roads, 64.11 km of easement lines, and 86.30 km of transmission lines. Combined with turbine pads and substations, the calculated direct disturbance footprint area for wind was 4.34 km<sup>2</sup>. On a per turbine basis (total = 397), this calculates to 0.01 km<sup>2</sup>, or 1 ha. Megawatts produced from these two projects range from 1.0 to 2.5, with an average of 1.4 MW/ha. These findings are therefore consistent with World Bank estimates (Ledec et al. 2011: 25): “The footprint of cleared natural vegetation from wind



**Fig. 6** Viewshed analysis of the PNGE study area from which wind turbines are visible

turbine platforms and interconnecting roads tends to be 1–2 ha/MW.” Furthermore, the wind footprint equals 526 SFs; with an average of 1.32 SFs per turbine pad.

### Transportation (non-energy) Disturbance

To get a truer picture of habitat fragmentation in PNGE, one has to look further than the energy production footprint and examine the transportation network. Road density is “the average total road length per unit area of landscape” such as km/km<sup>2</sup> and serves as “an important but crude measure to assess the potential impact of roads on local environments” (Forman et al. 2003: 9, 40). In our study area there were 1087.86 km of transportation roads (Weld County GIS) yielding a density of 0.52 km/km<sup>2</sup>. A value of 0.6 km/km<sup>2</sup> may be the maximum for a naturally functioning landscape that contains large predators (Forman et al. 2003), though coyotes are likely the largest predator here. The direct disturbance from non-energy-specific roads was 12.37 km<sup>2</sup>, or 0.59% of the area. This value provides an indication fragmentation based on transportation alone.

### Combined Oil and Gas, Wind and Transportation

The combined O&G, wind and transportation direct disturbance footprint equaled 34.20 km<sup>2</sup>, or 1.64% of the PNGE. Though the overall area of direct habitat loss is small, this network stretches across the PNGE and fragments the entire landscape. Incorporating a setback distance buffer of 100 m to the combined footprint above generated an estimated disturbance of 198.28 km<sup>2</sup>, 9.5% of the study area. With less than 10% of the PNGE disturbed by wind, O&G or non-energy roads, an initial picture emerges of large tracts of intact land.

### Core Areas

At 90.51% of the PNGE, this large amount of land remote from infrastructure (Weller et al. 2002) is deceiving since it

implies large of unfragmented land units. The opposite is true, with a total of 283 patches in the study area. Of those, 148 patches range from 0.5 to 169 km<sup>2</sup>, with an average patch size of 14.63 km<sup>2</sup> and patch density of 0.06 (see Fig. 7). Though about 95% of these patches were comprised of grasslands, this roadless area is quite fragmented (see Fig. 8). An alternative disturbance measure, GAP analysis data from the USGS (2017) regarding avoidance zones for the pronghorn, provides a less impacted scenario. Since the pronghorn is the largest mammal in the area, we used it as proxy for disturbance by calculating avoidance zones for the PNGE. Here, about 64 km<sup>2</sup> of land qualified as avoidance areas, while 99.72% of these were classified as low avoidance (see Fig. 9).

### Land Use Land Cover

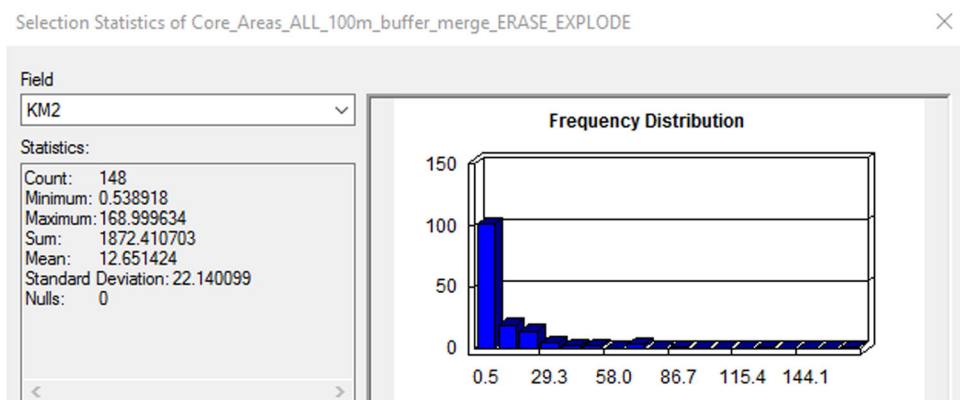
In the PNGE, the dominant LULC is grasslands/pasture, accounting for 93% of the area. Developed (urban) and agricultural land use account for almost 7% of the area, with minimal areas covered by barren/shrubland, forest, and open water/wetlands. The 93% grasslands is consistent for almost all the features: O&G Footprint, Wind Footprint, National Grassland Units, Oil Fields, Wind Buffered Footprint and Oil Buffered Footprint.

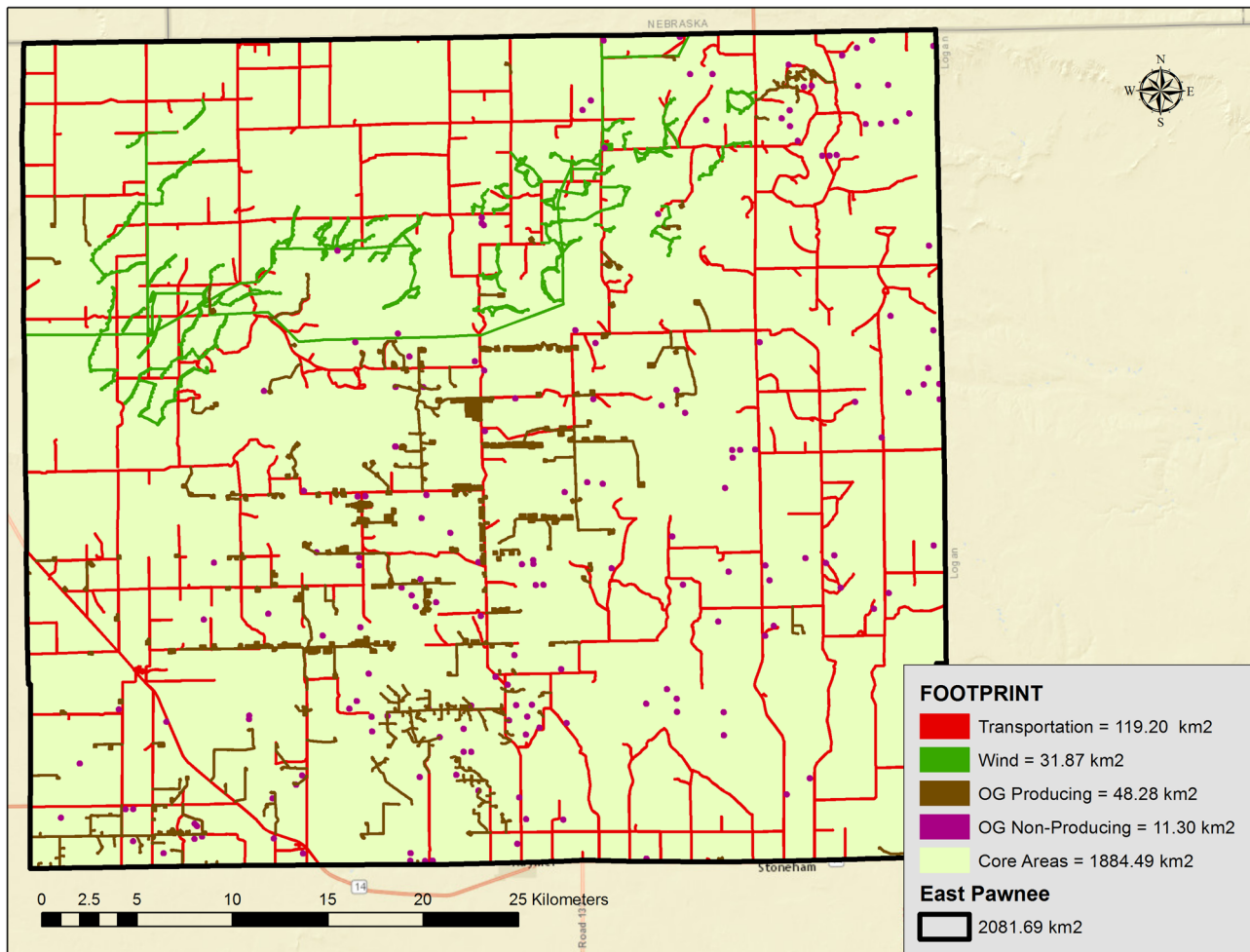
The exceptions are the transportation extended footprint and the combined (O&G producing and non-producing, wind and transportation) extended footprint. Here, because these areas were already developed, grasslands/pasture accounted for about 72 and 81%, respectively, of the LULC inside these footprints.

About 4% of the wind footprint occurred on agricultural land, both direct and extended, while 1.5% of O&G footprint affected farming. Thus energy development by far occurred on grasslands, *creating new disturbance*.

For core/roadless areas, the dominant LULC remaining was also grass/pasture, which is to be expected if these polygons of land represent roadless, natural features in the landscape.

**Fig. 7** Patch-size frequency distribution for core areas





**Fig. 8** The pattern and extent of the extended O&G (producing and non-producing), W-E and transportation footprint. The core, or roadless areas, appear as patches carved by the above footprint

Finally, the dominant agricultural activity on the grasslands is ranching. NASS 2016 data show that only 5% of the PNGE is dedicated to crops. Furthermore, locals do not consider grazing as land disturbance. Rather, it's a natural activity taking place for more than 100 years, ever since the first cattle drive reached Colorado from Texas around 1859 (Milligan et al. 2014) (Table 6).

## Discussion

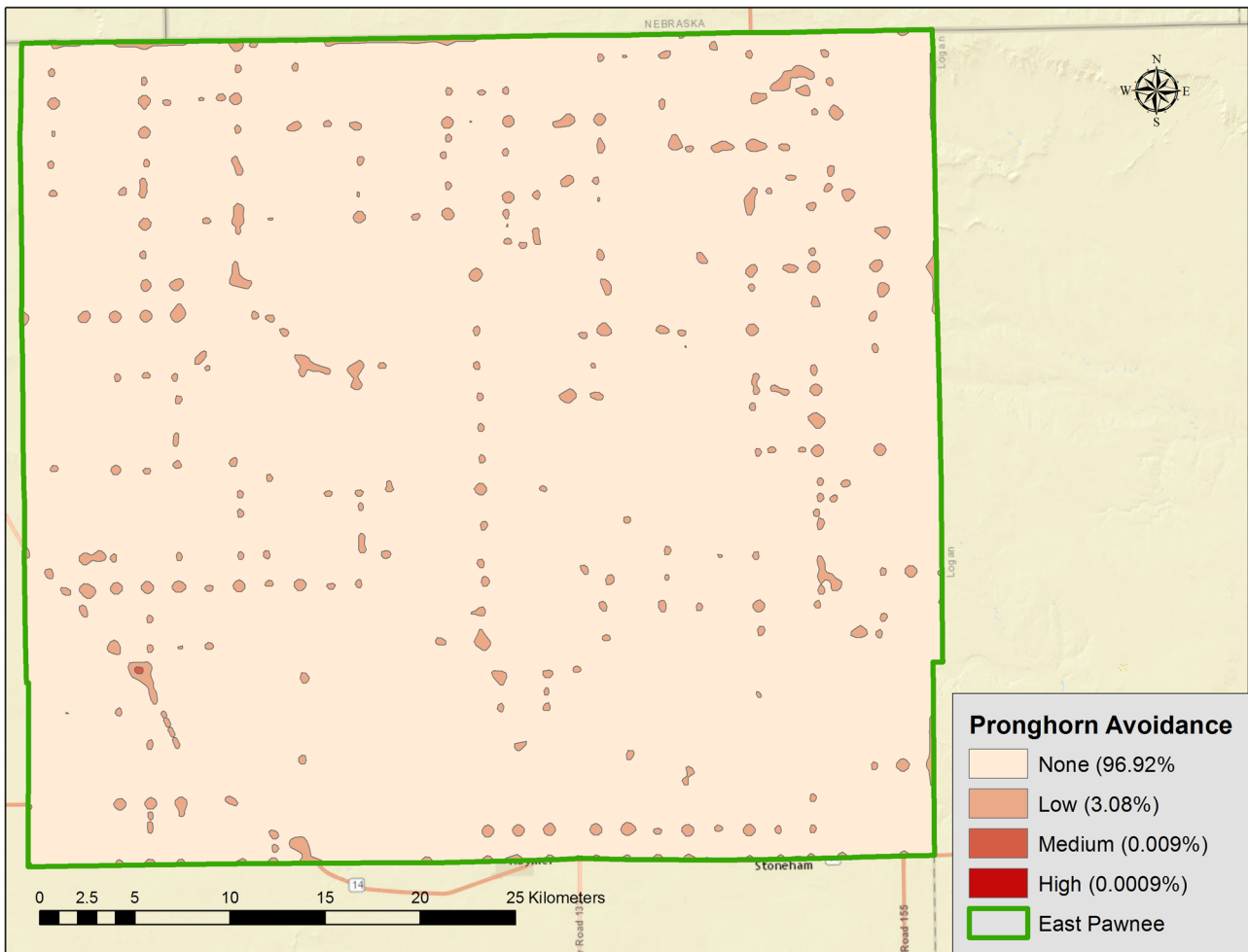
The combined energy production in this region (wind, oil, and gas) can create large-scale habitat fragmentation through many parts of the western US (east of the Rockies), but limited habitat loss. This is the central outcome of this energy research.

If looking to install W-E projects in the US, the best sites include large parcels of land with high winds, located in the Great Plains (McNew et al. 2014). This indeed is the case

with the Cedar Creek I and II wind farms in the high ridges of the PNGE (see Fig. 10).

Due to the spacing between wind turbine pads, O&G wellpads and the accompanying access roads, the footprint of energy development stretches out across the entire PNGE. This *network form*, as Forman et al. (2003: 9) describe, “determines the relative sizes, shapes, and arrangements of enclosed patches.” As Fig. 8 shows, the spatial arrangement and distribution of roadless areas (core areas) is a map of multiple small patches, none larger than 170 km<sup>2</sup>, or eight percent of the PNGE.

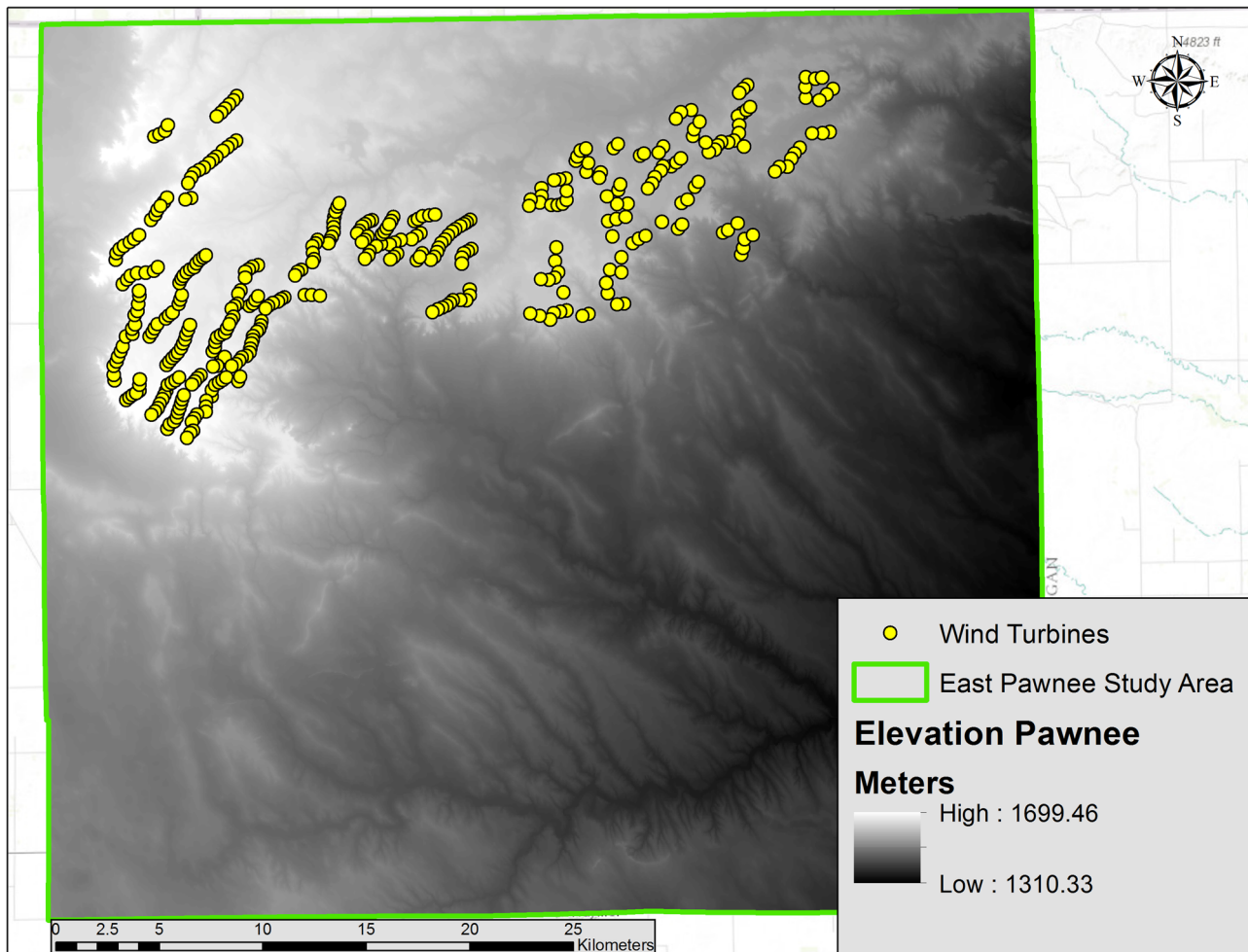
The W-E analysis includes electricity substations, transmission lines, and easements in which underground cables are buried. Over time the latter may return to natural vegetation and might be removed from the W-E footprint. The remaining pattern, nevertheless is still extensive due to the necessary spacing between turbines and the construction of access roads to each of these. Another consideration: in the naturally open grasslands and shrub-steppe ecosystems,



**Fig. 9** Pronghorn avoidance zones in the PNGE (Source: USGS 2017)

**Table 6** Land-use land-cover-percent of area

	Agriculture	Barren/ Shrubland	Developed	Forest	Grass/ Pasture	Open water/ Wetlands
PNGE study area	4.94	0.2	1.78	0.02	92.97	0.09
Oil & gas footprint (Producing)	1.48	1.21	3.36	0	93.87	0.08
Oil & gas footprint (Non-Producing)	0.94	0.1	0.65	0	98.32	0
Wind footprint	4.21	0.07	2.05	0	93.67	0
National grassland units	0.2	0.25	2.25	0	97.28	0.02
Oil fields	2.48	0.11	1.91	0.02	95.43	0.06
Transportation	2.96	0.06	44.00	0.01	52.89	0.08
Total footprint	2.28	0.49	17.46	0	79.70	0.06
Buffered						
Oil buffered footprint (Producing)	1.35	0.42	5.5	0	92.71	0.02
Oil buffered footprint (Non_Producing)	0.56	0.06	1.33	0	98.04	0
Wind buffered footprint	3.93	0.05	3.47	0	92.55	0
Transportation buffered footprint	4.50	0.09	23.05	0.03	72.23	0.1
Combined buffered footprint	3.61	.016	14.44	0.02	81.72	0.07
Core/Roadless areas	5.05	0.20	0.46	0.02	94.15	0.09



**Fig. 10** DEM of the PNGE and the location of wind turbines. The *lighter shaded areas* represent the higher elevations, which is where the wind farms are located

tall wind infrastructure may frighten birds and mammals from important habitat areas (Ledec et al. 2011). However, further research is needed, particularly since the Union of Concerned Scientist note that impacts to bird and bats from W-E “are relatively low and do not pose a threat to species populations” (UCS 2013). For tourists the ubiquitous visibility of these towers from many locations, including the Pawnee Buttes, may create what Carver et al. (2012) refer to *visual intrusion*.

Surprisingly, overall direct land disturbance from energy development is quite small in the PNGE. The combined wind and O&G energy disturbance footprint occupies less than 1% of the land (wind = 0.21%; oil and gas = 0.61%).

In Colorado, the recent passage of US Senate House energy bill not only supports research and development in clean energy technologies (US Senate Committee on Energy and Natural Resources 2016) but also provides export provisions to the liquefied natural gas sector that should streamline project approval (Snow 2016). This may well lead to increased fracking for natural gas (The Hill

2016), since export markets will progressively open up. Furthermore, the US Energy Information Administration (Sieminski 2016) forecasts that by 2040 as global energy demand rises, natural gas consumption will increase by 3% (from 23 to 26%), oil will decrease by 3% (33 to 30%) and renewable energy will rise by 4% (12 to 16%) (OGJ 2016; Sieminski 2016). Despite the growth in renewable energy demand, fossil fuels will continue to supply more than 75% of global energy (OGJ 2016; Sieminski 2016). Furthermore, natural gas is considered the clean alternative to coal and many new electricity-generating plants are fueled by gas, increasing demand, while driving coal mining down.

Simultaneously, major O&G exporting countries continue pumping at record production. Discussion among OPEC countries and other major producers to freeze or limit production has not resulted in any binding agreements. In fact Saudi Arabia oil production reached an all-time high in July 2016 (Spindle and Said 2016). Thus despite lower prices, O&G production will continue in the Colorado steppes and throughout the world. In the PNG, the Forest



Service predicts development will continue in the southern part of the area (Milligan et al. 2014). Understanding how to measure, monitor, and reduce the surface landscape footprint is paramount to reducing environmental effects such as habitat fragmentation, loss of biodiversity, and natural areas, thus increasing the sustainability of these activities—and contributing to the triple-bottom line approach. In the case of grasslands, these may be especially vulnerable to increased conversion based on commodity prices and land parcel productivity increases (Hill and Olson 2013).

### Recommendations

A key way to make energy development more sustainable and thus reduce the energy footprint, particularly for wind, is to site turbines on already disturbed (agricultural) land (Kiesecker et al. 2011). This is arguably easier to do with W-E, assuming strong winds are present in the area because oil extraction needs to take place near subsurface deposits—though horizontal drilling does allow access from several kilometers away.

W-E development will continue in Colorado in order to meet a 2007 state-adopted renewable portfolio standard which calls for 20% to 30% of energy produced by large utilities to originate from renewable resources (Colorado Senate Bill 13-252 2016; Durkay 2016; Power-Technology 2015b). Continued W-E development is expected in the northern part of PNGE (Milligan et al. 2014), and in fact only 13 km to the east, in the neighboring county of Logan, large wind projects located there contain 477 turbines as of 2014 (USGS 2015). A quick visual analysis of high resolution imagery indicates more wind turbines have been built here since.

Prime W-E locations are those with steady winds (at least 20 km/hr) (Pimentel et al. 2002), often located on ridges. This can lead to visual pollution since turbines are observable for quite a distance (Ferguson 2008).



**Fig. 11** the Pawnee Buttes, a landmark scenic location in the PNGE with a view of wind turbines in the background, June 2015

Such is the case in the PNGE, where wind turbines are located on the high ridges and therefore can be seen in over half of the territory. This includes the Pawnee Buttes, one of the most attractive landscape features in this area (see Fig. 11), which may be hard to photograph without catching turbines in the background. While some visitors may find wind turbines eye-catching, power-lines do affect scenic quality of valued landscapes (Milligan et al. 2014). Furthermore, noise, bird and bat mortality and disturbance to natural areas must be considered (not only from the turbines, but also the overhead power lines) (Ledec et al. 2011; UCS 2013). Locating structures at least 300 m away from nature reserves coupled with painted patterns and strobe lights on these structures can help reduce avian mortality (Pimentel et al. 2002; Sheppard et al. 2015).

Following suggestions by UCS (2013), establishing wind farms on already developed land, i.e., agricultural land, is the more sustainable approach. So is placing turbines on abandoned toxic industrial sites and brownfields (UCS 2013; NREL 2010). Depending on the type of crop planted, vegetables and cattle can be raised beneath the turbines, maximizing the use of converted land (Pimentel et al. 2002).

Finally, stakeholder engagement is important. In the town of Grover, Colorado, located between West and East Pawnee, and close to the Cedar Creek I wind farm, local citizens observe that they do not benefit from free or reduced electricity, despite living next door to the windmills (Counts, personal communication 2015). Furthermore, their local roads are being worn down from the maintenance vehicles that travel back and forth to the turbine pads. Grover's population of 145 (US Census Bureau 2016) would require about 483 KW to power the homes of all the inhabitants. Each nearby turbine provides at least 1000 KW (Power-Technology 2015a), thus the potential to deliver electricity to this community exists; alternately the wind project consortium could conceivably subsidize energy bills for these residents.

Regarding O&G development, careful site selection—away from water bodies and high ridges, as our findings in Russia suggest, no surface occupancy on protected and sensitive lands (as the FS suggests and has now mandated in the PNG), remediation of abandoned sites and roads, development on already disturbed areas and a clear understanding of the size and extent of the footprint are key to reducing landscape alterations. Since annual precipitation is minimal in the Colorado region, creeks can remain dry for years and site location near water bodies may be less important here than in the Russian study area.

Perhaps one of the more effective approaches to diminish O&G landscape disturbances, is to build fewer yet larger wellpads that allow multiple horizontal wells to be drilled from one site. Thus reserves from as far away as 3500 m can

be accessed from one location (CSUR 2015). Another strategy, pad drilling, allows operators to concentrate groups of wells at one location and then easily move the drilling rig, even a few meters away through hydraulic walking or skidding systems (EIA 2012). Because of this, sensitive surface areas can be avoided while still extracting hydrocarbons underneath. In fact just north of our study area in the Williston Basin, pad drilling accounts for about 75% of new wells (Preston and Kim 2016).

In this scenario, while the size of wellpad alterations increases, the number of disturbed patches is reduced (Milligan et al. 2014). Because the surrounding land in this checkerboard polygon of grassland is privately owned, continued or enhanced production from those sites can assure that federally owned surfaces will remain undisturbed from energy development (though private grasslands may become increasingly disturbed). Grazing, however, will likely continue on federal land.

Utilizing drones would greatly benefit energy landscape research by allowing researchers to examine a greater number of disturbed areas, especially those that are inaccessible to investigators. Advances in geoprocessing allow for video feeds from drones to be entered into a GIS and analyzed (ESRI 2017). During field visits near Orenburg Russia in October 2015, we observed research drones flying over private energy-production lands that were off limits to non-employees.

Regarding remediation, finding and removing abandoned pits is another way to reduce the O&G footprint. During our June 2015 and 2016 visits we found some secluded and abandoned wells containing open waste pits and evaporation ponds without any enclosures (see Fig. 12). According to Jones and Pejchar (2013: 3) “Reserve pits are now quickly becoming obsolete as many regulators and operators are adopting close-loop systems which eliminate the



**Fig. 12** Caption: reserve pits in an (apparently) abandoned and remote wellpad in the PNGE, June 2015

need for open pits.” Future visits should identify and rank abandoned pits in need of clean-up.

Detecting noise pollution resulting from energy development can help broaden our understanding of cumulative impacts. As we found out, the distance at which noise is discernible, from both wind and O&G is greatly affected by the winds blowing on these steppes. It’s also influenced by topography, whereby small rolling hills and valleys can enhance or mask noise. While several researchers note how O&G structures and accompanying noise can scare away large species such as mule deer (*Odocoileus hemionus*) and pronghorn (*Antilocapra americana*), the main effects measured focus on distance to roads and the resulting loss of habitat and fragmentation for these and other animal species (Sawyer et al. 2011; Wilbert et al. 2008; van der Ree et al. 2011; Weller et al. 2002; Hebblewhite 2008). Interestingly, Christie et al. (2016) studying pronghorn populations and oil development in western North Dakota, found that “pronghorn avoid human development and roads but not O&G wells,” (154) because of their location in high-value habitats. We also observed pronghorn near oil development in the PNGE, where the sound of compressors did not seem to frighten them away.

In conclusion, energy production activities, which can be clearly monitored using the methods proposed here, can promote energy independence alongside a more sustainable form of energy production by properly siting, monitoring and reducing the amount of land occupied in “energy sprawl” (Jones and Pejchar 2013). Policy makers, regulators and industry can utilize methods implemented in this study to enhance environmental performance standards that remain uniform across different locations where energy is produced. Removing the spatial variability inherent in state or country-specific regulations and using one approach greatly benefits industry by increasing certainty and efficiency in environmental, health and safety protocols. This in turn reduces legal exposure, which can run into the millions and billions of US dollars and can also help reduce negative press coverage, falling stock prices and confrontations with stakeholders and local inhabitants (Baynard 2011).

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**Conflict of interest** The authors declare that they have no competing interests.

## References

- 7 USC Section 1281 (1981). <https://www.gpo.gov/fdsys/pkg/STATUTE-95/pdf/STATUTE-95-Pg1213.pdf>. Accessed 10 Feb 2016
- 43 USC Section 161 (1862) Repealed. <http://uscode.house.gov/view.xhtml?req=43+section+161&f=treesort&fq=true&num=152&hl=true&edition=prelim&granuleId=USC-prelim-title43-section161>. Accessed 10 Feb 2016
- 114<sup>th</sup> Congress (2016) H.R.8- North American Energy Security and Infrastructure Act of 2015. <https://www.congress.gov/bill/114th-congress/house-bill/8/text>. Accessed 6 May 2016
- Ahmed SE, Souza Jr CM, Ribeiro J, Ewers RM (2013) Temporal patterns of road network development in the Brazilian Amazon. *Reg Env Change* 13(5):927–937. doi:10.1007/s10113-012-0397-z
- Bankhead-Jones Tenant Act (1937) 7 USC 1000, 1006, 1010-1012. [http://www.fs.fed.us/grasslands/resources/documents/primer/App\\_I\\_Pos\\_Legis\\_History.pdf](http://www.fs.fed.us/grasslands/resources/documents/primer/App_I_Pos_Legis_History.pdf). Accessed 10 Feb 2016
- Baynard CW (2011) The landscape infrastructure footprint of oil development: Venezuela's heavy oil belt. *Ecol Indic* 11(3):789–810. doi:10.1016/j.ecolind.2010.10.005
- Baynard CW, Ellis JM, Davis H (2013) Roads, petroleum and accessibility: the case of eastern Ecuador. *GeoJ* 78:675–695. doi:10.1007/s10708-012-9459-5
- Baynard CW, Schupp RW, Zhang P, Fadil P (2014) A geospatial approach to measuring surface disturbance related to oil and gas activities in West Florida, USA. *Adv Remote Sens* 3(2):77–93. doi:10.4236/ars.2014.32007
- Carver S, Comber A, McMorran R, Nutter S (2012) A GIS model for mapping spatial patterns and distribution of wild land in Scotland. *Landsc Urban Plan* 104:395–409
- Carver S, Tricker J, Landres P (2013) Keeping it wild: mapping wilderness character in the United States. *Journal Environ Manage* 131:239–255. doi:10.1016/j.jenvman.2013.08.046
- CDOT (Colorado Department of Transportation) (2011) Entire 2011 Construction Specification Book. [https://www.codot.gov/business/designsupport/2011-construction-specifications/2011-Specs/2011-specsbook/2011-Specs-Book.pdf/at\\_download/file](https://www.codot.gov/business/designsupport/2011-construction-specifications/2011-Specs/2011-specsbook/2011-Specs-Book.pdf/at_download/file). Accessed 22 Nov 2016
- Chibilyev AA (2013) The Steppe of Eurasia from Hungary to Mongolia. Vol 1. Orenburg: Russian Geographic Society, Institute of Steppe, the Ural Branch of Russian Academy of Sciences, pp 1–120.
- Christie KS, Jensen WF, Boyce MS (2016) Pronghorn resource selection and habitat fragmentation in North Dakota. *J Wildl Manage* 81(1):154–162. doi:10.1002/jwmg.21147
- COGCC (Colorado Oil and Gas Conservation Commission) (2016a) [http://cogcc.state.co.us/documents/data/downloads/gis/WELLS\\_SHP.ZIP](http://cogcc.state.co.us/documents/data/downloads/gis/WELLS_SHP.ZIP)
- COGCC (2016b) 2500' mandatory setback from oil and gas development. [http://cogcc.state.co.us/documents/library/Technical/Miscellaneous/Init\\_78\\_Proposed\\_2500ft\\_Setback\\_Assessment\\_Report\\_20160527.pdf](http://cogcc.state.co.us/documents/library/Technical/Miscellaneous/Init_78_Proposed_2500ft_Setback_Assessment_Report_20160527.pdf). Accessed 20 May 2016
- Colorado Senate Bill 13-252 (2016) Concerning measures to increase Colorado's renewable energy standard so as to encourage the deployment of methane capture technologies. [http://www.leg.state.co.us/clics/clics2013a/csl.nsf/fsbillcont3/D1B329AEB8681D4D87257B3900716761?Open&file=252\\_enr.pdf](http://www.leg.state.co.us/clics/clics2013a/csl.nsf/fsbillcont3/D1B329AEB8681D4D87257B3900716761?Open&file=252_enr.pdf). Accessed 5 May 2016
- CSUR (Canadian Society for Unconventional Resources) (2015) Understanding well construction and surface footprint. [http://www.csur.com/sites/default/files/Understanding\\_Well\\_Construction\\_final.pdf](http://www.csur.com/sites/default/files/Understanding_Well_Construction_final.pdf). Accessed 2 Feb 2016
- DOE (Department of Energy) (2014) Report: global share of renewable energy could double by 2030. <http://www.energy.gov/eere/vehicles/articles/report-global-share-renewable-energy-could-double-2030>. Accessed 5 May 2016
- DOE (Department of Energy) (2008) 20% wind energy by 2030. Increasing wind energy's contribution to U.S. electricity supply. <http://www.nrel.gov/docs/fy08osti/41869.pdf>. Accessed 5 May 2016
- Duram AL (1995) The national grasslands: past, present and future land management issues. *Rangelands* 17(2):36–42. <https://journals.uair.arizona.edu/index.php/rangelands/article/viewFile/11240/10513>
- Durkay J (2016) State renewable portfolio standards and goals. National Conference of State Legislatures (NCSL). <http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>. Accessed 5 May 2016
- EIA (2016a) US field production of crude oil. <http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRFPUS1&f=M>. Accessed 3 May 2016
- EIA (2016b) Cushing, OK WTI spot price FOB. <http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RWTC&f=D>. Accessed 3 May 2016
- EIA (2016c) US regular gasoline prices (dollars per gallon). <http://www.eia.gov/petroleum/gasdiesel/xls/pswrgvwall.xls>. Accessed 3 May 2016
- EIA (2016d) Rankings: crude oil production, April 2016. <https://www.eia.gov/state/rankings/#/series/46>. Accessed 14 Aug 2016
- EIA (2016e) Rankings: natural gas marketed production, 2014. <https://www.eia.gov/state/rankings/#/series/47>. Accessed 14 Aug 2016
- EIA (2012) Pad drilling and rig mobility lead to more efficient drilling. <https://www.eia.gov/todayinenergy/detail.cfm?id=7910#>. Accessed 12 Apr 2016
- ESRI (Environmental Services Resource Institute) (2016). ArcGIS for desktop software. 380 New York St., Redlands, CA. <http://www.esri.com/about-esri/>
- ESRI (2017) Drone2Map for ArcGIS. <http://www.esri.com/products/drone2map>. Accessed 21 Feb 2017
- Ferguson ARB (2008) Wind power: benefits and limitations. In: Pimentel D (ed) Biofuels, solar and wind as renewable energy systems. Springer Science+Business Media, pp 133–152
- FIFA (Federation Internationale de Football Association) (2015) Laws of the game 2015/2016. [http://www.fifa.com/mm/Document/FootballDevelopment/Refereeing/02/36/01/11/LawsofthegamewebEN\\_Neutral.pdf](http://www.fifa.com/mm/Document/FootballDevelopment/Refereeing/02/36/01/11/LawsofthegamewebEN_Neutral.pdf). Accessed 5 May 2016
- Finer M, Babbitt B, Novoa S, Ferrarese F, Pappalardo SE, De Marchi M, Saucedo M, Kumar A (2015) Future of oil and gas development in the western Amazon. *Environ Res Lett* 10:1–6. doi:10.1088/1748-9326/10/2/024003
- Finer M, Jenkins CN, Powers B (2013) Potential of best practice to reduce impacts from oil and gas projects in the Amazon. *PLoS One* 8(5):1–14. doi:10.1371/journal.pone.0063022
- Finer M, Jenkins CN, Pimm SL, Keane B, Ross C (2008) Oil and gas projects in the western Amazon: threats to wilderness, biodiversity and indigenous people. *PLoS One* 3(8):1–9. doi:10.1371/journal.pone.0002932
- Forman RTT, Sperlind D, Bissonnette JA, Clevenger AP, Cutshall CD, Dale VH, Fahrig L, France R, Goldman CR, Heanue K, Jones JA, Swanson FJ, Turrentine T, Winter TC (2003) Road ecology: science and solutions. Island Press, Washington, DC
- Forman TT, Alexander LE (1998). Roads and their major ecological effects. *Ann Rev Ecol and Syst* (29):207–231. doi:10.1146/annurev.ecolsys.29.1.207
- Hazlett D (1998). Vascular plant species of the Pawnee National Grasslands. US Department of Agriculture Rocky Mountain Research Station General Technical Report RMRS-GTR. [http://www.fs.fed.us/rm/pubs/rmrs\\_gtr017.pdf](http://www.fs.fed.us/rm/pubs/rmrs_gtr017.pdf)
- Hebblewhite M (2008) A literature review of the effects of energy development on ungulates: implications for central and eastern Montana. Report prepared for Montana Fish, Wildlife and Parks, Miles City, MT. <http://fwpiis.mt.gov/content/getItem.aspx?id=35572> Accessed 18 Feb 2017

- Heshmati A, Abolhosseini S, Altmann J (2015) The development of renewable energy sources and its significance for the environment. Springer, Singapore
- Hill MJ, Olson R (2013) Possible future trade-offs between agriculture, energy production, and biodiversity conservation in North Dakota. *Reg Env Change* 13(2):311–328. doi:10.1007/s10113-012-0339-9
- IRENA (International Renewable Energy Agency) (2014) IRENA maps out path to double the global share of renewable energy. [http://www.irena.org/News/Description.aspx?NTy-pe=A&mnu=cat&PriMenuID=16&CatID=84&News\\_ID=349](http://www.irena.org/News/Description.aspx?NTy-pe=A&mnu=cat&PriMenuID=16&CatID=84&News_ID=349). Accessed 5 May 2016
- Jacobson MZ, Delucchi MA, Bazouin G, Dvorak MJ, Arghande R, Bauer ZAF, Cotte A, de Moor GMTH, Goldner EG, Heier C, Holmes RT, Hughes SA, Jin L, Kapadia M, Menon C, Mullendore SA, Paris EM, Provost GA, Romano AR, Srivastava C, Vencill TA, Whitney NS, Yeskoo TW (2016) A 100% wind, water, sunlight (WWS) all-sector energy plan for Washington State. *Renew Energ* 86:75–88. doi:10.1016/j.renene.2015.08.003
- Jaffe, M (2015) Pawnee National Grassland oil and gas lease sale raises \$32 million. The Denver Post. 14 May. <http://www.denverpost.com/2015/05/14/pawnee-national-grassland-oil-and-gas-lease-sale-raises-32-million/>. Accessed 20 May 2016
- Janke JR (2010) Multicriteria GIS modeling of wind and solar farms in Colorado. *Renew Energ* 35(10):2228–2234. doi:10.1016/j.renene.2015.08.003
- Joly K, Nellemann C, Vistnes I (2006) A reevaluation of caribou distribution near an oilfield on Alaska's North Slope. *Wildl Soc Bull* 34(3):866–869. doi:10.2193/0091-7648(2006)34[866:AROCDN]2.0.CO;2
- Jones NF, Pejchar L (2013) Comparing the ecological impacts of wind and oil & gas development: a landscape scale assessment. *PLoS One* 8(11):1–12. doi:10.1371/journal.pone.0081391
- Kelly D (2014) 10 abandoned nuclear bunkers, missile silos & ammunition dumps. *Urban Ghosts*. <http://www.urbanghostsmedia.com/2014/12/10-abandoned-nuclear-bunkers-missile-silos-ammunition-dumps/2/>. Accessed 20 May 2016
- Kiesecker JM, Evans JS, Fargione J, Doherty K, Foresman KR, Kunz TH, Naugle D, Nibbelink NP, Niemuth ND (2011) Win-Win for Wind and Wildlife: A Vision to Facilitate Sustainable Development. *PLoS One* 6(4):1–8. doi:10.1371/journal.pone.0017566
- Koppang Z, Dunn S (2014) Small Colorado towns living with realities of oil, gas activity. *Niobranchalk.com*. <http://niobranchalk.com/news/id/78571/small-colorado-towns-living-realities-oil-gas-activity/>. Accessed 20 May 2016
- Kunz TH, Arnett EB, Erickson WP, Hoar AE, Johnson GE, Larkin RP, Strickland MD, Thresher RW, Tuttle MD (2007) Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. *Front Ecol Environ* 5(6):315–324. doi:10.1890/1540-9295(2007)5[315:eiowed]2.0.co;2
- Lane LJ, Nichols MH (1999) Semi-arid climates and terrain. In *Environ Geol*. Springer, Netherlands, pp 556–558. doi:10.1007/1-4020-4494-1\_300
- Larkin AM, Beier CM (2014) Wilderness perceptions versus management reality in the Adirondack Park, USA. *Landscape Urban Plan* 130:1–13. doi:10.1016/j.landurbplan.2014.06.003
- Leddy KL, Higgins KF, Naugle DE (1999) Effects of wind turbines on upland nesting birds in conservation reserve program grasslands. *Wilson Bull* 111(1):100–104
- Ledec GC, Rapp KW, Aiello RG (2011) Greening the wind: environmental and social considerations for wind power development. [http://www-wds.worldbank.org/external/default/WDSContentServer/WDS/IB/2012/01/09/000386194\\_20120109010935/Rendered/PDF/662330PUB0EPI00e0wind09780821389263.pdf](http://www-wds.worldbank.org/external/default/WDSContentServer/WDS/IB/2012/01/09/000386194_20120109010935/Rendered/PDF/662330PUB0EPI00e0wind09780821389263.pdf). 10.1596/978-0-8213-8926-3
- Lukawski MZ, Anderson BJ, Augustine C, Capuano LE, Beckers KF, Livesay B, Tester JW (2014) Cost analysis of oil, gas, and geothermal well drilling. *J Pet Sci Eng* 118:1–14. doi:10.1016/j.petrol.2014.03.012
- Lupp G, Konold W, Bastian O (2013) Landscape management and landscape changes toward more naturalness and wilderness: effects on scenic qualities—the case of the Müritzer National Park in Germany. *J Nat Conserv* 21:10–21. doi:10.1016/j.jnc.2012.08.003
- Marimuthu C, Kirubakaran V (2013) Carbon pay back period for solar and wind energy project installed in India: A critical review. *Renew Sustainable Energy Rev* 23:80–90. doi:10.1016/j.rser.2013.02.045
- McDonald RI, Fargione J, Kiesecker J, Miller WM, Powell J (2009) Energy sprawl or energy efficiency: climate policy impacts on natural habitat for the United States of America. *PLoS One* 4(8):1–11. doi:10.1371/journal.pone.0006802
- McNew LB, Hunt LM, Gregory AJ, Wisely SM, Sandercock BK (2014) Effects of wind energy development on nesting ecology of greater prairie-chickens in fragmented grasslands. *Conserv Biol* 28(4):1089–1099. doi:10.1111/cobi.12258
- Microsoft. (2016) Excel- Microsoft Office. Redmond, Washington
- Milligan J, Burd J, Philbrook K, Fullenkamp L, Coe A, Fairchild M, Miller D, Schroeder E, Entwistle D, Nieves L, Dobb J, Gunsalus C, Reichert R, Smith J, White M (2014) Pawnee National Grassland oil and gas leasing analysis. Draft environmental impact statement August 2014. [http://a123.g.akamai.net/7/123/11558/abc123/forestservic.download.akamai.com/11558/www/nepa/95573\\_FSPLT3\\_2324299.pdf](http://a123.g.akamai.net/7/123/11558/abc123/forestservic.download.akamai.com/11558/www/nepa/95573_FSPLT3_2324299.pdf). Accessed 10 Mar 2016
- Mjachina KV, Chibilyev AA (2015) Use of satellite data to identify steppe lands of the Orenburg Trans-Volga Region disturbed by oil development. *Geogr Nat Res* 36(4):135–141. doi:10.1134/s1875372815040095
- Mjachina KV, Baynard CW, Chibilyev AA (2013) Oil and gas development in the Orenburg region of the Volga-Ural steppe zone: qualifying and quantifying disturbance regimes. *Int Jour Sust Dev World Ecol* 21(2):111–126. doi:10.1080/13504509.2013.867908
- Müller A, Bøcher PK, Svenning J-C (2015) Where are the wilder parts of anthropogenic landscapes? A mapping case study for Denmark. *Landscape Urban Plan* 144:90–102. doi:10.1016/j.landurbplan.2015.08.016
- Murkowski L (2016) Murkowski: Alaska will greatly benefit from passage of bipartisan bill. United States Senator Lisa Murkowski for the State of Alaska. Press Releases. 20 Apr 2016. [http://www.murkowski.senate.gov/public/index.cfm/pressreleases?ContentRecord\\_id=85361549-958A-467D-AB7D-CDFCAB83F027](http://www.murkowski.senate.gov/public/index.cfm/pressreleases?ContentRecord_id=85361549-958A-467D-AB7D-CDFCAB83F027). Accessed 6 May 2016
- NAIP (National Agricultural Imagery Program) (2015) United States Department of Agriculture Farm Service Agency. NAIP Imagery. <http://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/index>
- NASS (National Agricultural Statistical Service) (2016) CropScape, Weld County, Colorado 2015. <https://nassgeodata.gmu.edu/CropScape/>
- NOAA (National Oceanic and Atmospheric Administration) (2017) New Raymer 21 N, CO US. <https://www.ncdc.noaa.gov/cdo-web/datatools/normals> Accessed 18 Feb 2017.
- NREL (National Renewable Energy Laboratory) (2010) Brownfield's bright spot: solar and wind energy. [http://www.nrel.gov/news/features/feature\\_detail.cfm/feature\\_id=1530](http://www.nrel.gov/news/features/feature_detail.cfm/feature_id=1530). Accessed 20 May 2016
- NTLCS (National Toxic Land/Labor Conservation Service) (2014) As above so below: three ragged tales of national security at the Pawnee National Grasslands. <http://www.nationaltlcservice.us/2014/07/as-above-so-below-three-ragged-tales-of-national->

- [security-at-the-pawnee-national-grasslands/](#). Accessed 3 Feb 2016
- OGJ (Oil & Gas Journal). (2016). EIA: oil market share to slip but stay strong. 11 May. <http://www.ogj.com/articles/2016/05/eia-oil-market-share-to-slip-but-stay-strong.html?cmpid=EnlDailyMay112016&eid=288133178&bid=1402232>. Accessed 12 May 2016
- Ondorff RR (1972) The large birds of prey of the Pawnee National Grassland: nesting habits and productivity, 1969-1971. Technical Report No. 151. Grassland Biome, U.S. International Biological Program. <https://dSPACE.library.colostate.edu/bitstream/handle/10217/15846/IBP151.pdf?sequence=1&isAllowed=y>. Accessed 7 Feb 2017
- Olson E (1997) National grasslands management: a primer. USDA Natural Resource Division Office of the General Counsel. [http://www.fs.fed.us/grasslands/resources/documents/primer/NG\\_Primer.pdf](http://www.fs.fed.us/grasslands/resources/documents/primer/NG_Primer.pdf)
- Pacific Power (2016) Cedar Creek wind farm. <https://www.pacificpower.net/env/bsre/bses/ccwf.html>. Accessed 7 Jan 2016
- Pimentel D, Herz M, Glickstein M, Zimmerman M, Allen R, Becker K, Evans J, Hussain B, Sarsfeld R, Grosfeld A, Seidel T (2002) Renewable energy: current and potential issues. *BioScience* 52 (12):111–1120. doi:10.1641/0006-3568(2002)052[1111:recapi]2.0.co;2
- Power-Technology (2015a) Cedar Creek wind farm, Colorado, United States of America. <http://www.power-technology.com/projects/cedarcreek/>. Accessed 5 May 2016
- Power-Technology (2015b) Cedar Creek II wind farm, Colorado, United States of America. <http://www.power-technology.com/projects/cedarcreekiiwindfarm/>. Accessed 5 May 2016
- Preston TM, Kim K (2016) Land cover changes associated with recent energy development in the Williston Basin; Northern Great Plains, USA. *Sci Tot Env* 566–567:1511–1518. doi:10.1016/j.scitotenv.2016.06.038
- Pruett CL, Patten MA, Wolfe DH (2009) Avoidance behavior by prairie grouse: implications for development of wind energy. *Conserv Biol* 23(5):1253–1259. doi:10.1111/j.1523-1739.2009.01254.x
- Rhoads D, Rhoads L (2013) Pawnee National Grassland history. USDA Forest Service Arapaho & Roosevelt National Forest Pawnee National Grasslands. [http://www.fs.usda.gov/detail/arp/about-forest/?cid=fsm91\\_058308](http://www.fs.usda.gov/detail/arp/about-forest/?cid=fsm91_058308). Accessed 20 May 2016
- Roso A, Duker RL (1988) The space center at Colorado Springs. *Soc Sci J* 25(4):477–484. doi:10.1016/0362-3319(88)90026-2
- Sawyer SC, Epps CW, Brashares JS (2011). Placing linkages among fragmented habitats: do least-cost models reflect how animals use landscapes? *Journal Applied Ecol* (48):668–678. doi:10.1111/j.1365-2664.2011.01970.x
- Shannon G, McKenna MF, Angeloni LM, Crooks K.R, Fristrup KM, Brown E, Warner KA, Nelson MD, White C, Briggs J, McFarland S, Wittermeyer G (2015) A synthesis of two decades of research documenting the effects of noise on wildlife. *Biol Rev* (26 June). doi:10.1111/brev.12207
- Sheppard JK, McGann A, Lanzone M, Swaisgood RR (2015) An autonomous GPS geofence alert system to curtail avian fatalities at wind farms. *Anim Biotelemetry* 3(1):1. doi:10.1186/s40317-015-0087-y
- Sieminski A (2016) International Energy Outlook 2016. U.S. Energy Information Administration. [http://www.eia.gov/pressroom/presentations/sieminski\\_05112016.pdf](http://www.eia.gov/pressroom/presentations/sieminski_05112016.pdf). Accessed 12 May 2016
- Snow N (2016) Senate approves broad bipartisan energy bill in an 85-12 vote. Oil and Gas Journal <http://www.ogj.com/articles/2016/04/senate-approves-broad-bipartisan-energy-bill-in-an-85-12-vote.html?cmpid=EnlDrillingMay62016&eid=288133178&bid=1396795>. Accessed 6 May 2016
- Spindle B, Said S (2016) Saudi output hits record. Wall Street Journal, 11 Aug., (CCLXVIII, 35). p 11
- The Hill (2016) Senate passes energy reform bill. <http://thehill.com/policy/energy-environment/276965-senate-passes-energy-reform-bill>. Accessed 6 May 2016
- Thirdtable (2013) Colorado's Nuclear Missile Silos. <http://www.thirdtable.com/Adopt-a-Silo/MissileMaps/colorado.html>. Accessed 20 May 2016
- Trimble D (1980) The geologic story of the Great Plains. US Department of Interior. Geological Survey Bulletin No. 1493. <https://pubs.usgs.gov/bul/1493/report.pdf>
- UCS (Union of Concerned Scientists) (2013) Environmental impacts of wind power. [http://www.ucsusa.org/clean\\_energy/our-energy-choices/renewable-energy/environmental-impacts-wind-power.html#references](http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-wind-power.html#references). Accessed 20 May 2016
- US Census Bureau (2016) Grover town, Colorado. <http://www.census.gov/search-results.html?q=grover+colorado&search.x=0&search.y=0&search=submit&page=1&stateGeo=none&searchtype=web&cssp=SERP>. Accessed 6 May 2016
- US Senate Committee on Energy and Natural Resources (2016) Cantwell leads passage of the first comprehensive, bipartisan energy bill since 2007. <https://www.energy.senate.gov/public/index.cfm/2016/4/cantwell-leads-passage-of-the-first-comprehensive-bipartisan-energy-bill-since-2007>. Accessed 12 Dec 2016
- USDA (United States Department of Agriculture) 1965. The land utilization program 1934-1964: origin, development, and present status. Agriculture Economic Report No. 85. <http://naldc.nal.usda.gov/naldc/download.xhtml?id=CAT87201807&content=PDF>. Accessed 8 Feb 2016
- USDA FS (Forest Service) (2015) Pawnee National Grassland oil and gas leasing analysis final record of decision. <http://www.fs.usda.gov/detail/arp/news-events/?cid=STELPRD3829411>. Accessed 20 May 2016
- USDA FS (2016a) Pawnee National Grassland Oil and Gas Information. <https://www.fs.usda.gov/detail/full/arp/home/?cid=stelprdb5410781>. Accessed 7 Feb 2017
- USDA FS (2016b) Administrative forest boundaries. FS Geodata Clearinghouse. [http://data.fs.usda.gov/geodata/edw/edw\\_resources/fc/S\\_USA.AdministrativeForest.gdb.zip](http://data.fs.usda.gov/geodata/edw/edw_resources/fc/S_USA.AdministrativeForest.gdb.zip)
- USGS (United States Geological Survey) (2015) Onshore industrial wind turbine locations for the United States to March 2014. <https://catalog.data.gov/dataset/onshore-industrial-wind-turbine-locations-for-the-united-states-to-march-201453ff7#sec-dates>
- USGS (2017) National Gap Analysis Program (GAP) Species Data Portal. <https://gapanalysis.usgs.gov/species/data/download/>. Accessed 12 Feb 2017
- Van der Berg AE, Koole SL (2006) New wilderness in the Netherlands: an investigation of visual preferences for nature development landscapes. *Landscape Urban Plan* 78(4):362–372. doi:10.1016/j.landurbplan.2005.11.006
- van der Ree R, Jaeger JAG, van der Grift EA, Clevenger AP (2011) Effects of roads and traffic on wildlife populations and landscape function: road ecology is moving toward larger scales. *Ecol & Soc* (16:1) Art 48. doi: <http://dx.doi.org/10.5751/ES-03982-160148>
- Venier LA, Thompson ID, Fleming R, Malcolm J, Aubin I, Trofymow JA, Langor D, Sturrock R, Patry C, Outerbridge RO, Holmes SB, Haeussler S, De Grandpré L, Chen HYH, Bayne E, Arseneault A, Brandt JP (2014) Effects of natural resource development on the terrestrial biodiversity of Canadian boreal forests. *Environ Rev* 22 (4):457–490. doi:10.1139/er-2013-0075
- WCS (Wildlife Conservation Society) (2011) Greater Yasuni- Napo moist forest landscape conservation area (Ecuador), 1–24. [https://rportal.net/library/content/global-conservation-program/gcp-closeout-reports/greater-yasuni-napo-moist-forest-landscape-conservation-area-ecuador/at\\_download/file](https://rportal.net/library/content/global-conservation-program/gcp-closeout-reports/greater-yasuni-napo-moist-forest-landscape-conservation-area-ecuador/at_download/file). Accessed 12 Feb 2016

- Weld County GIS (2015) GIS data. [https://www.weldgov.com/departments/geographic\\_information\\_systems/gis\\_data/](https://www.weldgov.com/departments/geographic_information_systems/gis_data/).
- Weld County Colorado (2016) GIS Data. [https://www.weldgov.com/departments/geographic\\_information\\_systems/gis\\_data/](https://www.weldgov.com/departments/geographic_information_systems/gis_data/)
- Weller C, Thomson J, Morton P, Aplet G (2002) Fragmenting our lands: The ecological footprint of oil and gas development. A spatial analysis of a Wyoming gas field. The Wilderness Society, Washington D.C, p 1–24. [https://wilderness.org/sites/default/files/fragmenting-our-lands\\_0.pdf](https://wilderness.org/sites/default/files/fragmenting-our-lands_0.pdf)
- Wilbert M, Thomson J, Culver NW (2008) Analysis of Habitat Fragmentation from Oil and Gas Development and Its Impact on Wildlife: A Framework for Public Land Management Planning. The Wilderness Society, Washington D.C, pp 1–31. <http://www.fws.gov/southwest/ES/Documents/Oil-Gas-Fragmentation-Wilbert%20et%20al%202008.pdf> Accessible
- Wilderness Society (2015) Too wild to drill. The Wilderness Society, Washington, DC, p 1–19. <https://wilderness.org/sites/default/files/TooWildtoDrill.pdf>
- Winder VL, Carrison KM, Gregory AJ, Hagen CA, Haukos DA, Kesler DC, Larsson LC, Matthews TW, McNew LB, Patten MA, Pitman JC, Powell LA, Smith JA, Thompson T, Wolfe DH, Sandercock BK (2015) Factors affecting female space use in ten populations of prairie chickens. *Ecosphere* 6(9):1–17. doi:10.1890/es14-00536.1
- Yoshioka T, Aruga K, Nitami T, Kobayashi H, Sakai H (2005) Energy and carbon dioxide (CO<sub>2</sub>) balance of logging residues as alternative energy resources: system analysis based on the method of a life cycle inventory (LCI) analysis. *J For Res-JPN* 10 (2):125–134. doi:10.1007/s10310-004-0126-7
- Yu F, Guo Y, Le-Nguyen K, Barnes SJ, Zhang W (2016) The impact of government subsidies and enterprises' R&D investment: A panel data study from renewable energy in China. *Energ Policy* 89:106–113. doi:10.1016/j.enpol.2015.11.009
- Zuckerman G (2014) *The Frackers: the Outrageous Inside Story of the New Billionaire Wildcatters*. Penguin, New York, pp 1–423