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A Comparison of the Impacts of Wind Energy and Unconventional Gas Development on Land-use and Ecosystem Services: An Example from the Anadarko Basin of Oklahoma, USA

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Abstract

The United States energy industry is transforming with the rapid development of alternative energy sources and technological advancements in fossil fuels. Two major changes include the growth of wind turbines and unconventional oil and gas. We measured land-use impacts and associated ecosystem services costs of unconventional gas and wind energy development within the Anadarko Basin of the Oklahoma Woodford Shale, an area that has experienced large increases in both energy sectors. Unconventional gas wells developed three times as much land compared to wind turbines (on a per unit basis), resulting in higher ecosystem services costs for gas. Gas wells had higher impacts on intensive agricultural lands (i.e., row crops) compared to wind turbines that had higher impacts on natural grasslands/pastures. Because wind turbines produced on average less energy compared to gas wells, the average land-use-related ecosystem cost per gigajoule of energy produced was almost the same. Our results demonstrate that both unconventional gas and wind energy have substantial impacts on land use, which likely affect wildlife populations and land-use-related ecosystem services. Although wind energy does not have the associated greenhouse gas emissions, we suggest that the direct impacts on ecosystems in terms of land use are similar to unconventional fossil fuels. Considering the expected rapid global expansion of these two forms of energy production, many ecosystems are likely to be at risk.

Keywords Land-use · Ecosystem services · Unconventional gas · Wind energy · Anadarko Basin · Woodford Shale

Introduction

Energy consumption is closely tied to economic growth, making the need for abundant and inexpensive energy production increasingly important in the competitive global economy (Scarrow and Crenshaw 2015). The United States has the second highest energy consumption of any country on Earth and one of the highest per capita demands for energy (IEA 2016). Energy production has shifted rapidly in recent years as the demand for energy increases and energy technology evolves. In particular, the United States has recently increased its use of unconventional gas and wind resources (EIA 2015).

Unconventional gas production, defined in this paper as the combined use of horizontal drilling and hydraulic fracturing (i.e., fracking) to extract gas from low porous rock (Reinsalu and Aarna 2015), has increased dramatically in the last decade (EIA 2014). The development of unconventional gas resources has led to an almost 40% increase in the US natural gas production since 2005, which is equal to the equivalent of 1.86 billion new megawatts (MW) of annual electricity, even as conventional gas extraction has been declining (EIA 2015). The result is that the United States is now the number one producer of natural gas in the world. Much of this new gas production is being diverted to electricity production (Wang et al. 2014), although it also has many other industrial uses.

In addition to unconventional gas, wind energy production has also increased dramatically in the United States (EIA 2016a), showing a 400% increase, from 5 million MW per month in 2008 to 20 million MW per month in 2016, which equals 180 million new MW per year (EIA 2016b). A total of $103 billion has been invested in the US wind

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energy since the 1980s (Wiser and Bolinger 2014) and the United States has over 75,000 wind turbines (Wiser and Bolinger 2015). Some states now produce a large proportion of their electricity from wind energy. For example, this value is >25% for Iowa (EIA 2016c).

Both fracking and wind energy have associated environmental and ecological costs. Unconventional gas production is highly controversial, with concerns about water and air pollution, public health effects, noise and light pollution, seismic effects, and increases in greenhouse gas emissions (Ellsworth 2013; Shonkoff et al. 2013; Jackson et al. 2014; Rosenberg et al. 2014). Wind turbines have been associated with environmental and social costs as well, including increased wildlife mortality, noise pollution, and reduction of property values (Barrios and Rodriguez 2004; Smallwood 2007; Kunz et al. 2007; Colby et al. 2009; Hoen et al. 2011). Wind energy does have an advantage of low carbon emissions and has been touted as a means to combat global climate change (Wang et al. 2014). One major effect shared by both unconventional gas and wind development is land-use impacts (McDonald et al. 2009; Johnson 2010; Allred et al. 2015; Trainor et al. 2016). Habitat loss and fragmentation are major contributors to species decline and extinction and are considered the biggest immediate threats to many species (Dramstad et al. 1996), although climate change may be a larger long-term threat (Javeline et al. 2013). Unconventional gas and wind have been developed intensively mostly in rural areas, including many areas of high ecological value that have seen little energy development in the past. For instance, the biodiverse central Appalachian region (i.e., Pennsylvania, West Virginia, and eastern Ohio), which has been recovering from the past deforestation (Alig and Butler 2004; Drummond and Loveland 2010) is being heavily impacted by gas, and to a lesser extent, wind development (Jones et al. 2015), although more wind development is predicted in the near future (Johnson 2010).

Natural habitats provide extensive ecosystem services to humanity, by some estimates equaling a monetary value larger than the current gross world product (de Groot et al. 2012; Costanza et al. 2014). Ecosystem services include provisioning (e.g., food, water, raw materials), regulating (e.g., climate), habitat (e.g., genetic diversity), and cultural services (e.g., recreation). Development of natural habitat by humanity therefore has a measurable impact on the ability of the natural world to provide these services, what we refer to as “ecosystem services costs.”

In this study, we examined the land-use changes caused by unconventional gas and wind development in the Anadarko Basin of the Woodford Shale in west-central Oklahoma. We then calculated the ecosystem services costs associated with these land-use changes. We chose this region as a case study because the area has seen the rapid development of both unconventional gas wells (from 0 to 228 wells) and wind turbines (from 0 to 418 turbines) from 2008 to 2015. We measured the amount of land developed and the associated ecosystem services costs and standardized these measurements on a per unit basis (i.e., well or turbine) and on a per unit energy produced (i.e., gigajoules). Our goal was to determine which type of energy development is associated with higher environmental costs, in terms of habitat modification and ecosystem services due to land-use changes.

Materials and Methods

Study Area

We chose the Anadarko Basin of the Woodford Shale formation in west-central Oklahoma (Fig. 1) as the sampling location because it is a good model for the changing US energy patterns. Although the area has a long history of conventional oil and gas drilling, more recently there has been a boom in unconventional gas and wind energy development, resulting in a high number of unconventional wells and wind farms (Fig. 2). Nationally, unconventional gas development began in 2004 (Grieser 2011), but wells in the Anadarko portion of the Woodford Shale were constructed after 2008. Wind farm construction began in 2010 in this region (Kansas Energy Information Network 2016). Both forms of development continue to this day, although unconventional gas drilling has recently declined to low levels (Oklahoma Corporation Commission, Oil and Gas Division 2016). The area is characterized by rolling plains, in its natural condition, covered mostly by mixed-grass prairie and small areas of scrub oak woodlands (Oklahoma Forestry Services 2007). Most of the area is sparsely populated by humans and large areas of the region today are dedicated to row crop cultivation and cattle grazing (Oklahoma Department of Transportation 2010).

Land-use Measurements

To measure the land-use impacts of unconventional gas development, we examined satellite views utilizing current and historical satellite imagery from Google Earth Pro™. We used ArcMap to create Keyhole Markup Language (KML) layers that outlined the Anadarko Basin, United States Geological Survey quadrangles, and unconventional well locations within the Woodford Shale. To collect a representative sample of wells, we measured the land-use changes due to well development in a series of randomly selected quadrangles within the region until we had

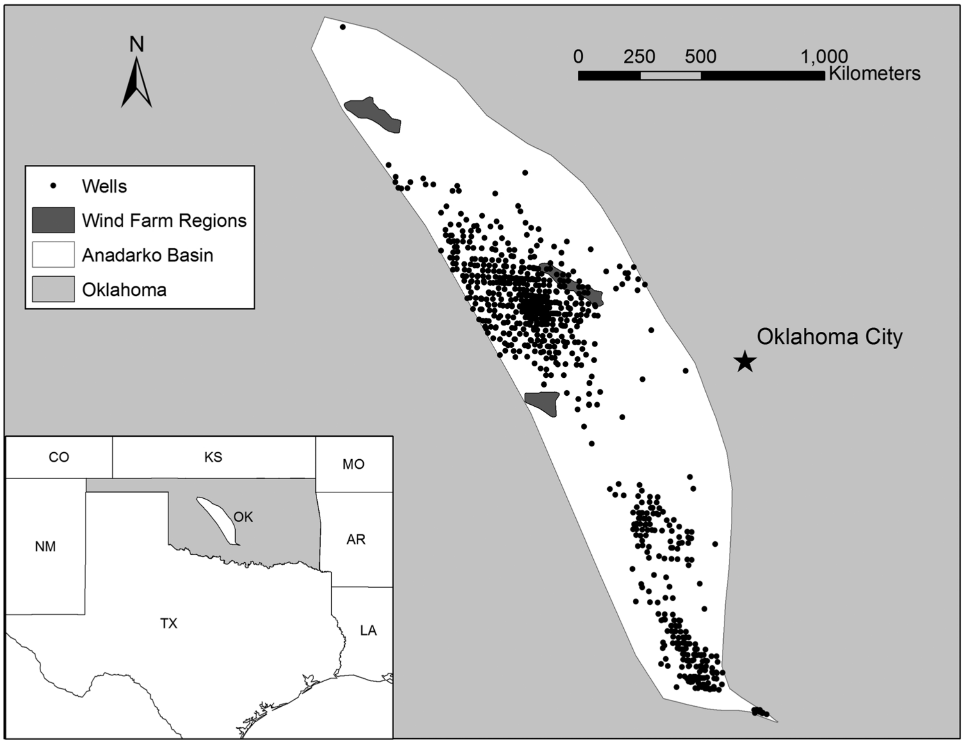

Fig. 1 Unconventional well locations and commercial wind farm regions within the study area of the Anadarko Basin in the Woodford Shale of west-central Oklahoma, USA

measured over 200 wells. Measured impacts include well pads, roads, pipeline right-of-ways, and associated structures (e.g., compressor stations). These measurements were manually taken by hand-drawing polygons around affected areas with the Measure Tool in Google Earth Pro™.

To measure land-use impacts of wind energy, we measured all commercial turbines constructed within the Anadarko Basin. Measured impacts included turbine pad, relay stations, and roads constructed to wind infrastructure. As in the gas well procedure, we manually determined the area occupied by the different structures using the Measure Tool in Google Earth Pro™.

For both gas and wind development, land was classified as fully developed (i.e., converted from natural or semi-natural habitat to artificial structure) or modified (i.e., converted or degraded from existing habitat to some other habitat type). Examples of areas fully developed include well or turbine pads (which are covered in gravel), and an example of modified habitat is pipeline right-of-ways that convert woodland or forest into pasture land (Moran et al. 2015). We calculated the mean land-use impact based on a per well or per turbine basis. Though we found no evidence of wind turbines and gas wells sharing associated structures, often we found that multiple gas wells or multiple turbines shared associated structures (e.g., many wind turbines or gas wells on one road). Thus, it was not possible to determine the variation in land use for individual wells or turbines (i.e., no practical way to calculate land-use variance per unit).

Energy and Ecosystem Services Calculations

We selected a priori a 25-year life span for both gas wells and wind turbines. Since both sources of energy are in their infancy, the lifespans of unconventional wells and industrial turbines are unknown. Industry estimates for gas wells have a high variance, with some estimates as high as 40 years (Hughes 2013), while other researchers have suggested that unconventional gas wells will have a much shorter lifespan, perhaps <20 years (U.S. Geological Survey Oil and Gas Assessment Team 2012; Hughes 2013). Industry estimates of wind turbine lifespans have been in the 20–25-year range (Staffell and Green 2014). We therefore, recognize that the time frame of 25 years is somewhat arbitrary, but it serves as a reasonable estimate to compare the two sources of energy production.

Historical gas well production data, measured in thousands of cubic feet (mcf) from year of first production through 2015 were obtained from Oklahoma Corporation Commission's Well Data System (Oklahoma Corporation Commission, Oil and Gas Division 2016). Since gas well production for individual wells starts very high and then declines in a predictable pattern (Agarwal et al. 1998; Guo et al. 2016), an exponential decay regression was modeled from the accumulated data of the sample wells, sorted by year of first production (2009–2015). We sorted wells by year of first production because of the high variation in initial production values, which is typical for a gas field as it is developed (Baihly et al. 2010). For the unconventional gas industry, initial production values have tended to

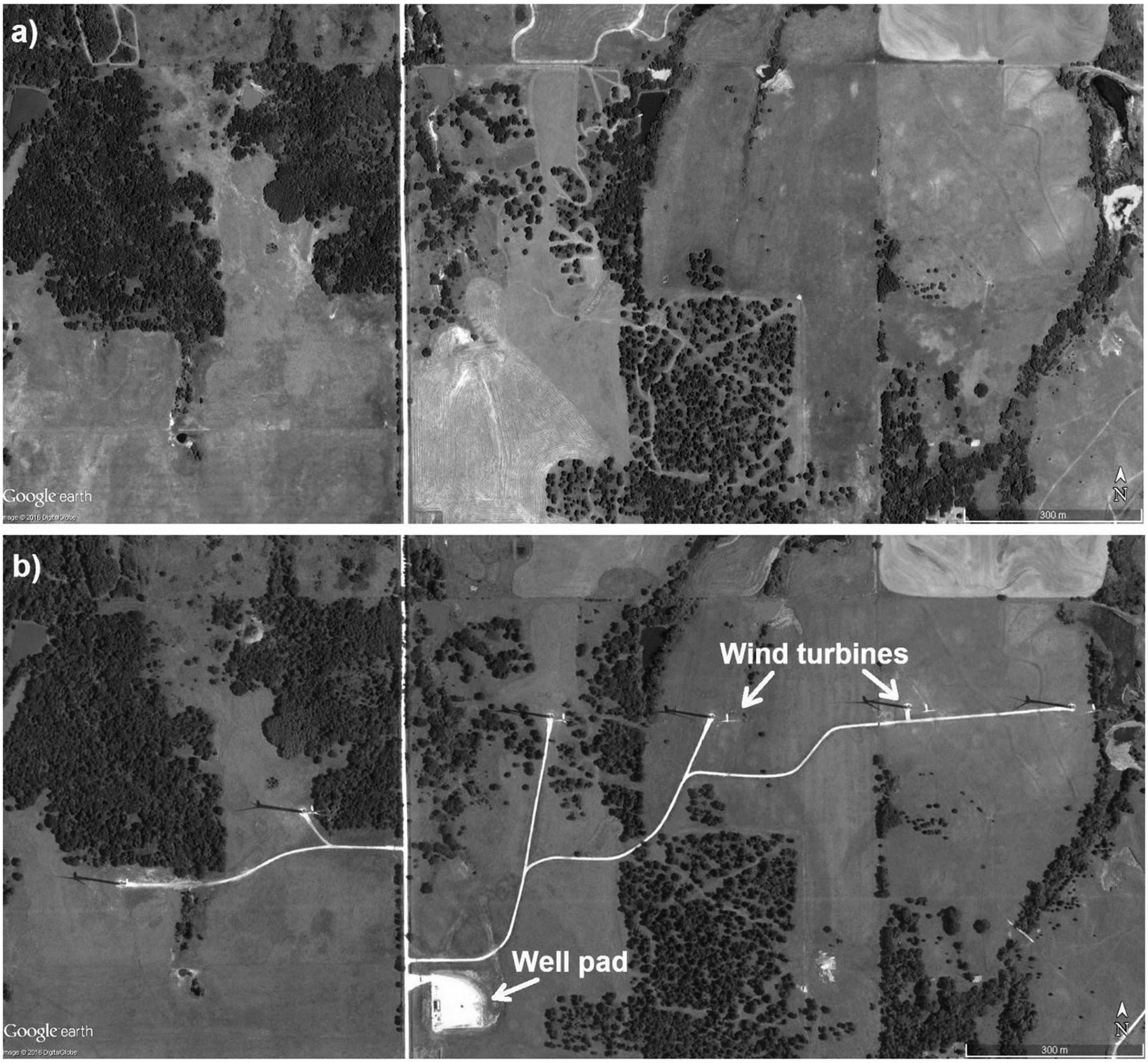

Fig. 2 Examples of satellite imagery from **a** 2010 and **b** 2015 showing land cover changes from unconventional gas and wind energy development in the Anadarko Basin of west-central Oklahoma, USA

increase over time, reflecting improvements in drilling and hydrofracturing methods (Baihly et al. 2010), which in turn changes lifetime well production values. Wells completed from 2012 to 2015 were analyzed as one group because of the limited data points (i.e., only 4 years of data) available to construct a model production curve. We integrated the area under the regression curve from year 0 to the year 25 to estimate the total output of the well over its expected lifetime using:

$$\text{Total gas production} = y_0/k\left(e^{25k} - 1\right) \qquad (1)$$

where $y_0 = y$-intercept in mcf, and $k =$ the modeled slope-parameter for the exponential decay curve fit for gas production data, and $e =$ base of the natural logarithm.

Weighted means were calculated to determine the average lifetime production of gas wells in the Anadarko Basin and then divided by 25 to get the mean production per well per year. Gas production was converted from mcf to Gigajoules to standardize the amount of energy present in estimated gas production.

Historical turbine production data from date of first full year of production through 2015 were recorded from the U. S. Energy Information Administration's Electricity Data Browser (EIA 2016b). We divided the number of megawatt hours (Mwh) produced by the entire field by the number of turbines present to determine average energy production per turbine per year. Since individual turbine measurements were not available, we were not able to determine variance in turbine energy production. For the entire Anadarko Basin, we calculated weighted means for annual energy production of all turbines present. We converted Mwh to Gigajoules to standardize the energy content for the amount of electricity produced.

We obtained habitat-specific ecosystem services (ES) values from a previous study (Moran et al. 2017). In that paper, habitat types overlapping oil and gas regions in the United States were identified (i.e., grassland/pasture, intensive agriculture, temperate forest, woodland). Ecosystem services values were then acquired by reviewing the literature and then used to calculate a mean ES value for each habitat type (a technique commonly utilized in ecosystem services literature, e.g., Costanza et al. 2014). This value was assumed to be uniform across each habitat. While this assumption is a simplification, there are not enough studies to calculate a meaningful measure of variation within each habitat. All ES values, including provisioning (e.g., food), regulating (e.g., nutrient cycling), habitat (e.g., gene pool protection), and cultural (e.g., recreation) services as described in the de Groot et al. (2010) template, were incorporated into the calculated costs. We assumed that fully developed habitat lost all ecosystem services, so the ES cost was the original value of the habitat. We assumed modified habitat still possessed ES values, so the cost of that modification was calculated as the difference in ES value between the new habitat and original habitat (Moran et al. 2017).

Annual ES costs per unit (well or turbine) were calculated by multiplying the number of hectares developed for each respective habitat by its estimated ES value (from Moran et al. 2017) and summing the values of each habitat. We then calculated the ES cost on a per gigajoule basis to acquire a standard ecosystem cost per unit of energy produced. In all calculations, monetary values were adjusted to USD 2015.

Results

Unconventional gas development had a land-use impact that was about three times larger than wind energy development, as measured on a per unit basis (i.e., per well or per turbine, Table 1). Most of the land in the Anadarko portion of the Woodford Shale is composed of lands dedicated to intensive row crop agriculture or natural (albeit grazed) temperate grasslands/pasture, so it was unsurprising that these were the major habitats developed. However, the proportion of habitat types developed was different between the two types of energy production, with unconventional gas wells primarily developing agricultural lands (over 75%, Table 2). Conversely, the wind turbines primarily developed grasslands/pasture (57%). In total, about 70% of the habitat developed by the wind industry was natural or semi-natural, while only 24% was natural or semi-natural for the gas wells. Woodland and forest, which made up small proportions of the habitat in the region, were developed in similar amounts by both forms of energy production.

The average energy production per year (based on 25-year unit lifespans) was about twice as high for gas wells compared to wind turbines. When ecosystem services costs were measured on a per turbine or per well basis, gas wells had about twice the impact. However, when measured on a per Gigajoule basis, the ecosystem services costs were almost equal (Table 3). Even though wind turbines developed a much smaller amount of land, they produced less energy and

Table 1 Comparison of amount of habitat developed and modified by recent unconventional gas compared to wind energy in the Anadarko Basin of west-central Oklahoma

	Hectares per gas well	Hectares per turbine
Habitat developed		
Intensive agriculture	0.820	0.091
Grasslands/pasture	0.224	0.177
Woodland	0.024	0.035
Forest	0.006	0.007
Total developed	1.074	0.310
Habitat modified		
Forest modified	0.022	0
Woodland modified	0.016	0
Total modified	0.038	0
Total developed and modified	1.112	0.310

Table 2 Habitat proportion developed in unconventional gas development compared to wind turbines in the Anadarko Basin of west-central Oklahoma

Proportion of habitat developed	Gas well	Wind turbine
Intensive agriculture	0.76	0.29
Pasture/grasslands	0.21	0.57
Woodland	0.02	0.11
Forest	0.01	0.02

Table 3 Comparison of energy production and ecosystem services (ES) costs between wind turbines and unconventional gas wells in the Anadarko Basin of west-central Oklahoma

Energy source	Gigajoules/unit/year	ES costs/unit/year	ES costs/gigajoule
Turbine	23,551.2	$769.00	$0.0326
Well	49,675.8	$1675.00	$0.0337

All ES values in 2015 USD

tended to impact habitats of much higher ES values (grassland/pasture) compared to gas wells, which predominantly impacted intensive agricultural lands (Table 1).

Discussion

Our results show that the land use of these two types of energy development, although occurring in the same geographical region, have substantially different ecological effects and potentially different socioeconomic effects because of different development patterns. Unconventional gas well development had the largest proportional impact on intensive agricultural land (i.e., row crops), and relatively smaller effects on the natural and semi-natural areas. Therefore, we suspect that current gas development could be having a negative impact on farming communities by the removal of land with higher agricultural and economic value (Hitaj 2014). Future development could exacerbate this trend, although drilling rates have declined dramatically, and there are indications that unconventional gas production from the Woodford Shale may have already peaked (Hughes 2014). Intensive agricultural lands in this area of Oklahoma are typically located in bottomlands and relatively level areas, presumably because of the higher soil fertility and ease of plowing, respectively. Gas wells were preferentially situated in the same areas, likely because of the lower costs of well pad and gas infrastructure construction. This trend appears consistent with results from other oil and gas basins, such as the Bakken area of North Dakota (Preston and Kim 2016)

By contrast, wind development had the largest proportional impact on natural and semi-natural habitats, in particular grasslands and pastures, although the absolute area of these habitats developed was still lower than gas wells on a per unit basis. Wind turbines developed a much smaller amount of intensive agricultural land, both on an absolute and proportional basis. Although most natural grasslands in the region are grazed by cattle or harvested for hay (except small areas in parks and preserves), they still contain relatively high levels of biodiversity and contain species of conservation concern or recreational value (Asner et al. 2004). The results of our study are specific for this region, but perhaps valid for similar habitats found in the Great Plains of the North America and throughout the globe (e.g., steppes of Iberia, Laiolo and Tella 2006). Analysis of wind energy impacts in forested habitats found double the land-use changes per turbine (Johnson 2010), presumably because much more forest has to be cleared for supporting structures of the industry (e.g., power lines). A recent study of unconventional gas production also found large differences in land-use impacts depending on geographic location (Moran et al. 2017).

In our study, wind turbines produce less energy (averaged over a 25-year period), but also have a much smaller footprint. However, when we measured ecosystem services costs associated with land-use changes on a per unit energy basis, the impacts are very similar, although still marginally higher for gas wells. Therefore, both unconventional gas development and wind development vary depending on impact parameter. In this region, wind turbines clearly use less land per turbine (compared to a per well basis), but the land they develop has higher ecological and conservation value and they produce less energy over time. This pattern results in almost equal ecosystem services costs caused by the land-use changes.

Any deviation from the a priori decision to utilize the 25 life span for both gas wells and turbines would have a dramatic effect on our results. If wind turbines have a lower life span than predicted, their land-use impact would be much greater on a per unit energy basis since there would be fewer years of production. Conversely, if wind turbines have a longer life span, or if they are replaced at the same sites without additional land disturbance, their impact would be much lower compared to gas wells. We also assumed turbine production would be constant over time. Aging components could reduce turbine efficiency and performance, although by how much over the long-term is highly uncertain (Staffell and Green 2014). Results would also be affected by the reclamation of abandoned gas wells or turbines back into natural habitat, although the history of industry reclamation, in terms of efforts or restored habitat quality, is mixed (Mitchell and Casman 2011). Therefore, our calculations of land-use impact on an energy production basis are more speculative and may explain why our values deviate from other published values (McDonald et al. 2009). We argue that our estimates on a per-unit basis are more substantiated since they are direct measurements and make no assumptions on future production. It should also be noted that fossil fuel (and therefore energy production) amounts vary dramatically depending on the geological formations. The Woodford Shale is on the lower end of the production range compared to other shale gas basins in the United States (Baihly et al. 2010). Comparisons within other basins are therefore likely to produce a variety of results.

Because of their land-use impacts and subsequent ecosystem services costs, we argue that both unconventional gas and wind development are having substantial ecological effects and potentially important socioeconomic effects. Wind energy has often been touted as an excellent source of "clean" energy because of its reliability, abundance, drastically lower greenhouse gas emissions, and very low levels of pollution (Şahin 2004; Herbert et al. 2007), although there have been concerns about direct wildlife mortality (Barrios and Rodriguez 2004; Kunz et al. 2007; Smallwood

2007). As our data show, wind energy effects on land-use and ecosystem services will be substantial and perhaps nearly as high as the development occurring because of the "fracking" revolution. Since wind energy is likely to develop more natural lands of higher ecological value, effects on wildlife could be profound. Since grasslands have already been drastically reduced by agricultural development, wind energy that preferentially targets the remaining natural grasslands could have negative effects on many endangered or declining grassland specialists (Askins et al. 2007; Swengel et al. 2011). Even if the land-use changes could be minimized through wise planning, the mere presence of wind turbines can negatively affect some wildlife. For example, turbines appear to negatively affect prairie chickens (*Tympanuchus* spp.), because of their aversion to tall structures where birds of prey often perch (Pruett et al. 2009). Future wind expansion would be an increasing threat to this declining species. High rates of bat mortality at turbines (Baerwald et al. 2008) are another cause of concern, which could exacerbate declines in species already at high risk from white-nosed syndrome (Blehert et al. 2009).

According to our data, unconventional gas development in the Anadarko Basin mostly affects intensive agricultural lands. While this pattern indicates the ecological impact of gas could be smaller than that of wind, the socioeconomic impacts could be greater through the loss of valuable croplands. In addition to the direct land-use impacts on agriculture, unconventional oil and gas have been linked to water and soil pollution, toxic effects on livestock, and general disruption of agricultural activities (Hitaj 2014). Furthermore, when a "split estate" situation exists (i.e., mineral and surface right are under different ownership), legal and civil conflicts have arisen (Fitzgerald 2010). These types of issues are typically smaller for wind energy since it is generally non-polluting and wind energy royalties always benefit the surface rights owner (Jacquet 2012; Weber et al. 2013).

Our study shows that unconventional gas and wind energy developments have a considerable effect on the land-use and ecosystem services of the Anadarko Basin of Oklahoma. The benefits and drawbacks of each source vary depending on the parameter of interest. Both energy sources are expected to expand across Oklahoma and throughout the United States in the near future (Trainor et al. 2016). In particular, the Great Plains is currently having a boom in both wind and unconventional oil and gas activity so there could be a disproportionate impact on grassland habitats, which in many cases are already highly modified and fragmented by agriculture. Wind energy is already expanding rapidly across the globe (Saidur et al. 2010; Leung and Wang 2012) and unconventional oil and gas production is also expected to expand into other regions of the world, including many ecological valuable habitats (Allred et al. 2015; Trainor et al. 2016). During the planning phases of this expansion, we urge stakeholders to incorporate lost ecosystem services into cost-benefit analyses. While the effects on air quality, water quality, and human health are sometimes considered along with economic impact, ecosystem services are often ignored. We argue that incorporating ES into such analyses would provide a more accurate and realistic assessment of the true value of these new energy developments. When this development proceeds, we urge governments and regulatory agencies to be aware of these impacts and develop appropriate oversight and legal frameworks that can mitigate the damage of these forms of energy and maximize their benefit to society.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethical Standards This study complies with all US laws. All appropriate approvals were obtained for the research. No animals were utilized.

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