



The threat of energy diversification to a bioregion: a landscape-level analysis of current and future impacts on the US Chihuahuan Desert

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Abstract

Landscapes are being impacted by rapid change, especially by diversifying energy industries. As this process occurs, habitats with little development and fragmentation are now facing increasing anthropogenic change. We studied current patterns of land use and ecosystem services costs of energy development and predicted future impacts in the US Chihuahuan Desert. We measured land developed and modified by oil and gas, wind, and solar industries and mapped levels of development and fragmentation across the US Chihuahuan Desert, followed by an estimation of annual energy-related ecosystem services costs. Based on energy resource estimates, we then projected future risk of development in the bioregion. The oil and gas industry has developed and fragmented about 27% (58,000 km²) of the US Chihuahuan Desert. Wind and solar comprise small amounts of development and fragmentation. We estimated annual ecosystem services costs of all energy industries at 180 million USD, concentrated in climate regulation, raw materials, and cultural services. Two-thirds of the desert remains relatively unfragmented in a contiguous corridor along the western portion of the bioregion. However, this corridor is threatened by energy expansion, especially wind and solar energy. With this expansion, the bioregion could become highly fragmented and continuity of habitats compromised. We suggest conservation efforts focus on the remaining corridor, while future energy development should occur in areas already highly modified by energy infrastructure. With continuing expansion and diversification of global energy sources, our findings in the Chihuahuan Desert could represent threats to other ecologically valuable bioregions that have historically experienced little industrial development.

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Introduction

Historically, the major causes of land use change and habitat alteration in many ecosystems have been agriculture and urban expansion (Vitousek et al. 1997; Lambin et al. 2001; Foley et al. 2005). In most parts of the temperate world, however, the amount of land devoted to agricultural is either stable or declining (Benayas et al. 2007), while urban expansion remains a threat (Seto et al. 2012). In recent years, the energy industry has become the largest source of land use change (in terms of newly developed land area) in some countries, especially as new energy sources (e.g., unconventional oil and gas, wind, and solar) increase in scope (Fthenakis and Kim 2009; Pocewicz et al. 2011; Trainor et al. 2016; Fisher and Burton 2018; Howden et al. 2019). Particularly concerning is that many ecoregions that have historically experienced minor human development and have existed as de facto wilderness areas may now be exposed to

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rapidly changing land use (Pocewicz et al. 2011). For instance, much of eastern Russian has remained a sparsely populated wilderness but recently has seen massive increases in petroleum development (Walker et al. 2006, 2010; Kumpula et al. 2011). This pattern may be particularly acute for deserts, which tend to be sparsely populated and unsuitable for intense agriculture, but excellent locations for energy industries, especially wind and solar (Jacobson and Delucchi 2011; Pocewicz et al. 2011).

Currently, the largest land use changes in the USA are occurring because of urban expansion (Foley et al. 2005) and energy development (Trainor et al. 2016). While past and current energy-related land use impacts have been mostly from oil and gas, the energy market is now diversifying to include renewables, which can also have a large land use footprint (Allred et al. 2015; Trainor et al. 2016). For instance, wind and solar energies develop and fragment extensive areas of land and may have land use impacts and ecosystem service costs similar to, or greater than, fossil fuel activity (Saidur et al. 2011; Davis et al. 2018). Because of their extensive sprawl, wind and solar energy may have 25× and 3× more landscape impact, respectively, compared to unconventional gas in terms of both direct footprint and fragmentation effects (Trainor et al. 2016).

Natural and semi-natural landscapes provide a wealth of societal benefits, often referred to as ecosystem services (Costanza et al. 1997; de Groot et al. 2012). Therefore, development and fragmentation of landscapes have measurable costs to society, including loss of food production, raw materials, regulating services (e.g., carbon cycle), and recreational value (Haddad et al. 2015). While development often adds economic value, the simultaneous loss of ecosystem services is an externality that is often disregarded (de Groot et al. 2010).

Ecosystem services vary across different biomes (Costanza et al. 2014). While ecosystem services patterns have been studied intensively in many bioregions, deserts have been largely neglected, perhaps because they are considered low productivity environments. However, deserts cover about 14% of the terrestrial world (Costanza et al. 2014), contain a wealth of biodiversity (Johnston 1977; Safrieli et al. 2005), and support unique cultural environments (Tyler 1975; Ezcurra 2006). Because of their harsh climates, deserts are often relatively intact and unfragmented compared to more productive environments (Curtin et al. 2002). Recently, however, some deserts have been experiencing rapid industrial growth, especially in the renewable energy sector, which tends to be economically feasible in these environments (Pasqualetti 2001; Jacobson and Delucchi 2011).

In North America, the Chihuahuan Desert fits these characteristics (Taylor et al. 2017) and may be emblematic of other parts of the world that have high-energy resources and are therefore experiencing energy-related industrial expansion. Recently, an intact portion of the Chihuahuan Desert was

analyzed for its ecosystem services (Taylor et al. 2017), which were indeed found to be considerably lower than other ecosystems. Despite this difference, the Chihuahuan Desert still provides important climate regulation, raw materials, cultural services, and biodiversity. This location is one of the highest diversity deserts in North America (Dinerstein et al. 2000; Hernández et al. 2001; Hoyt 2002) and contains many rare species and distinctive biological communities. The region has a unique historical and cultural landscape (Tyler 1975) and important renewable resources such as food (mostly cattle ranching, Holechek 1992; Taylor et al. 2017), fiber (Nobel and Quero 1986), and other products (e.g., *Candelilla* wax, Arato et al. 2014). Additionally, the region has important scientific value for understanding evolutionary patterns, climate history, and ecological processes (Brown and Zeng 1989; Buck and Monger 1999; Zink 2002; Alvarado-Cárdenas et al. 2013) and it contains some important surviving desert wildlife populations (Onorato et al. 2004; Hellgren et al. 2005; Holbrook et al. 2012). Though deserts likely have lower ecosystem services overall, they are generally very sensitive to human activity and often slower to recover from disturbance than other ecosystems (Scheffer et al. 2001).

Because of its dry climate, the Chihuahuan Desert has not had extensive agricultural development other than cattle grazing (Holechek 1992) and some locally intensive crops in landscapes suitable for irrigation (Ganjegunte and Clark 2017). However, the region has experienced substantial modification from the oil and gas industry, most notably within the Permian Basin of Texas and New Mexico. Due to the sunny and windy environment (NREL 2015), solar and wind energy have also begun to expand into this bioregion. These activities change habitat (Hernandez et al. 2014; Davis et al. 2018) by completely converting some lands to human structures (e.g., oil and gas well pads, Jones et al. 2015; Pierre et al. 2018; Wolaver et al. 2018a, b), reducing habitat quality (e.g., pipelines), and increasing fragmentation (e.g., road networks). These alterations to the landscape can cause considerable impacts on ecosystem services. Moran et al. (2017) estimated the ecosystem services costs of unconventional oil and gas development (defined as horizontal drilling and hydraulic fracturing) in major US production areas and found that annual costs are over \$250 million USD. However, at the time of publication, desert ecosystem services had not been estimated. With a recent publication of ecosystem services for a relatively intact portion of the Chihuahuan Desert (Taylor et al. 2017), estimates for the impact of various sources of energy development can now be calculated for this region.

To make informed decisions about how to proceed with energy development, cost-benefit analyses that monetize societal impacts are needed. Environmental impact statements prepared by government or private agencies provide qualitative cost-benefit analyses for oil and gas drilling (USDA 2018; USDI and BLM 2018), but they fall short in monetizing

environmental and social impacts of energy development. Using an ecosystem services framework, we attempted to calculate the indirect monetary values of the environmental, social, and cultural impacts of energy-related conversion of natural landscapes into energy infrastructure. Therefore, our analysis is similar to cost-benefit analyses performed to determine the net societal impact of federal environmental regulations (EPA 2011).

The goals of this study were to determine how current land use patterns and ecosystem services have been affected by energy development in the US portion of the Chihuahuan Desert, predict future patterns of energy activity in the region, and explore the conservation implications of both the current and predicted development patterns. We first measured current development and fragmentation patterns due to a variety of development sources, which included urban, agricultural, oil and gas, wind, and solar, with a detailed focus on the three energy sources. We utilized these land use change measurements to determine the ecosystem services costs of each source of energy development. We then used energy resource databases to predict locations where future land use change due to energy development is likely to occur. The current land use impact patterns were used to identify areas that remain relatively intact and could be conserved as biological corridors to maintain connectivity with other regions. Our hope is that by examining the impact to land use patterns and their respective ecosystem services costs, long-term planning may be undertaken to conserve this important bioregion. This approach to assessment and the associated conservation efforts could act as a blueprint for long-term bioregion protection of other deserts across the world.

Materials and methods

Study area

Our study site was the US portion of the Chihuahuan Desert, which covers 214,000 km² in parts of western Texas, southern New Mexico, and southeastern Arizona. The Chihuahuan Desert extends into north-central Mexico to form the largest desert in North America. Topographical variation supports three major habitat types: desert shrubland, desert grassland, and desert woodland, each of which varies in ecosystem service values (Taylor et al. 2017). The US portion of this bioregion is characterized by large areas of desert shrubland and desert grassland, with smaller areas of desert woodland in higher elevations. The region is sparsely populated, with only one large city (i.e., El Paso), and most of the area is dedicated to cattle ranching. There are also several globally important conservation areas (e.g., Big Bend National Park).

To establish the geographical extent of our study area, we imported shapefiles with boundaries for Level III Ecoregions (EPA 2013a) and USGS 7.5-min quadrangles (USGS 2016) into ArcMap (ESRI 2012). Using the Clip tool, we clipped the quadrangle shapefile to the Chihuahuan Desert boundary as defined by its Level III Ecoregion designation, which gave us a total of 1098 quadrangles in our study region. Additionally, we clipped a shapefile for the Level IV Ecoregions (EPA 2013b) to the Chihuahuan Desert boundary, and using vegetative characteristics, we reclassified each ecoregion according to the three major habitat types. The Rio Grande Floodplain ecoregion was not included in reclassification because it does not easily fit the three habitat types, covers a very small area of the Chihuahuan Desert, and contains little energy-related infrastructure (Fig. S1 of Online Resource 1).

Measurement of current energy impacts

To determine the effect of oil and gas on land development and fragmentation, we randomly selected 20 of the total 1098 quadrangles, which is a sample that represents about 2% of our study area (about 4300 km²). Within each quadrangle, we used the Ruler tool in Google Earth Pro (Google, Inc. 2017) to draw a polygon around each fragment, which was defined as contiguous land in its natural condition. We considered any boundary between natural habitat and human created/modified habitat as the edge of a fragment. These boundaries included lands developed (e.g., roads, well pads, other energy infrastructure, any human structures) and modified lands (e.g., pipeline right-of-ways, intensive agricultural areas; Fig. S2 of Online Resource 1). For each polygon fragment, we recorded the area and perimeter (i.e., edge).

To determine well counts in each quadrangle, we accessed the database of DrillingInfo.com, a fossil fuel industry well database (DrillingInfo.com 2017). We searched the database and counted all oil and gas wells that were completed by the end of 2016, regardless of active/inactive status. Wells that are classified as plugged and abandoned or inactive often remain on the landscape long after production ends and continue to have land use impacts (McClung and Moran 2018). We excluded wells that had been permitted, but not completed by 2016, since the majority of these wells had not yet made an impact on the landscape. We divided oil and gas drilling into two types: conventional and unconventional. Conventional wells were defined as those that use vertical drilling, which was the most common method used in the past century. Unconventional wells were defined as those that utilize horizontal drilling, most of which also use hydraulic fracturing (commonly referred to as fracking), a process that has expanded dramatically recently (Jackson et al. 2014; Moran et al. 2017). In total, there were 3008 wells located in our 20 sampled quadrangles, about 1% of the total wells for the study area. In the Chihuahuan Desert, there have been 224,170

conventional and 51,889 unconventional wells drilled since 1900 (DrillingInfo.com 2017; Fig. S1 of Online Resource 1).

For each sampled quadrangle, we then calculated the median fragment size, which was compared to the well count using a simple regression model. Since there was evidence of an exponential relationship, well count and median fragment size were \log_{10} -transformed prior to analysis. We also performed a linear regression on well count versus total edge habitat per quadrangle. From the results of the fragment regression analysis from the sample quadrangles, we used the generated linear equation and well counts to estimate the fragmentation level of each quadrangle in the Chihuahuan Desert. The y -intercept was the estimated fragmentation level in the absence of oil and gas development, which we classified as “background” fragmentation. From the equation of the linear regression, we then estimated the number of wells that cause three levels of fragmentation: 1–49%, 50–89%, and > 90% reduction in median fragment size. Those quadrangles with no wells were classified as “none,” although they would still have development and fragmentation from other anthropogenic sources.

To calculate the development and modification footprint of oil and gas wells, we used current satellite views of each sample quadrangle and Level IV Ecoregions to measure the amounts of our three specific habitat types that were converted per well using the same methods as fragment measurements above and as in previous publications (Moran et al. 2015; Cox et al. 2017; Moran et al. 2017; Davis et al. 2018). From these measurements, we determined the amount of land developed (i.e., completely converted to human structures) and modified (i.e., habitat converted to different plant cover). Total number of wells was mapped onto the three types of habitat to determine habitat-specific land use impacts (Fig. S1 of Online Resource 1).

For solar and wind energy measurements, we located all installations for solar ($N=17$) and wind ($N=6$) in the region (EIA 2017). For each, we measured land development with the same methods as oil and gas. Fragmentation was measured for each wind development area, but not for solar installations since solar panels tend to be highly concentrated and located directly along existing roads (i.e., they do not sprawl). Because there are only a few current wind energy and solar sites in the Chihuahuan Desert, there were not enough replicates to perform regression analyses on turbine or solar array count versus fragmentation level at the quadrangle level.

The habitat modifications of oil and gas, wind, and solar were used to estimate ecosystem services costs due to land use change with the same methods as in Moran et al. (2017). As in other publications (Cox et al. 2017; Moran et al. 2017; Davis et al. 2018), we assumed developed landscapes (i.e., completely converted from natural habitat to human structures) possessed zero ecosystem services, while modified habitat retained 50% of its ecosystem services. We chose the 50%

value for modified habitats so that results would be comparable with the previous studies (Moran et al. 2015, 2017), but we recognize that this value is arbitrary. Habitats modified by oil and gas development most likely have reduced ecosystem services through reductions in native plant cover, increases in invasive species, negative wildlife impacts, and changes in hydrology and soil (reviewed in Jones et al. 2015), but estimates of ecosystem services losses have been rarely quantified. Habitat-specific ecosystem service values for Chihuahuan Desert (Level IV bioregions, EPA 2013b) were obtained from Taylor et al. (2017) and standardized to 2016 USD using the US inflation rate since 2015 (i.e., the date utilized in Taylor et al. 2017). Valuation methods for each of the 22 ecosystem services varied according to strategies commonly utilized in published ES literature (Table S1 of Online Resource 1). Since ecosystem services estimates for the Rio Grande Floodplain Ecoregion have not been published, we could not determine the value of this habitat. Few wells exist in this habitat (Fig. S1 of Online Resource 1), so its exclusion likely has little impact on our estimates of ecosystem services costs.

Measurement of current impacts from other sources of land use change

Urban and agricultural expansions have also contributed to the modification and development of land in the Chihuahuan Desert. To evaluate these impacts, we directly measured the area of land developed by all urban establishments and intensive agriculture (e.g., row crops) by hand-drawing polygons around these areas using the Ruler tool in Google Earth Pro. All other land within the Chihuahuan Desert boundary lacking any impacts from energy development or fragmentation, urban expansion, and agricultural industries was considered to be in its natural state. However, cattle grazing is extensive in the region, and although this activity does not necessarily contribute much to development and fragmentation, it does have considerable ecosystem impacts (Buffington and Herbel 1965; Nash et al. 1999; Holechek et al. 2003).

The last source of potential fragmentation is the controversial border wall proposal (Harriss 2017; Roche et al. 2017). A pedestrian border wall that prohibits the movement of all terrestrial animals already exists in small portions USA-Mexico portion of the Chihuahuan Desert. Other areas contain vehicular barriers, but we assumed these structures do not prohibit the movement of most animals. We utilized topographical data obtained by the Bernard and Audre Rapoport Center for Human Rights and Justice (2018) to map locations on Google Earth Pro of the current border wall. We assumed that the wall, if completed as proposed, would span the entire USA-Mexico border region of the Chihuahuan Desert.

Predicting future impacts

From the data on energy development and fragmentation, urban development, intensive agricultural areas, and the current border wall, we constructed a map showing current areas of the Chihuahuan Desert that are highly impacted by human activity. We then mapped areas we consider to have high potential for future energy development. While the exact amount of future development is impossible to predict, and not likely to fully develop and/or fragment the entire high resource areas, we attempted to identify regions that have the highest risk to be impacted in ways similar to current energy developments. To predict future oil and gas impacts, we searched by all oil and gas leases in our study area that were signed between 2013 and 2017 (DrillingInfo.com 2017) and assumed these areas have geology that economically support future drilling. To predict future wind farm construction, we mapped the areas within the region that have at least 6.4 m/s of wind speed at 50 m in height (NREL 2009, 2012a, b), a resource level considered adequate for industrial wind farms (DoE 2008). To predict future solar energy development, we mapped the mean daily energy availability from sunlight (DoE 2011). Practically all of the Chihuahuan Desert has at least 6.5 kW/m²/day of solar radiation (NREL 2012c), which is considered the minimum for industrial solar facilities to be economically feasible (Pletka and Finn 2009). We then assumed the highest three categories (6.93–7.17 kW/m²/day) were the most likely areas to experience future development. It should be noted that some solar facilities already exist outside of our highest three categories, so our estimate of solar expansion may be conservative. It is likely that wind and solar development is also affected by proximity to existing infrastructure (e.g., transmission lines, roads; González et al. 2011), but we limited our estimates to natural resource availability, since infrastructure availability can change over time with increased development. The current development and fragmentation were then combined with our prediction of future energy and border wall development to illustrate which areas of the region are at highest risk. Figure 1 demonstrates our overall strategy for quantifying the current and future land use impacts and ecosystem services costs of energy development in the bioregion.

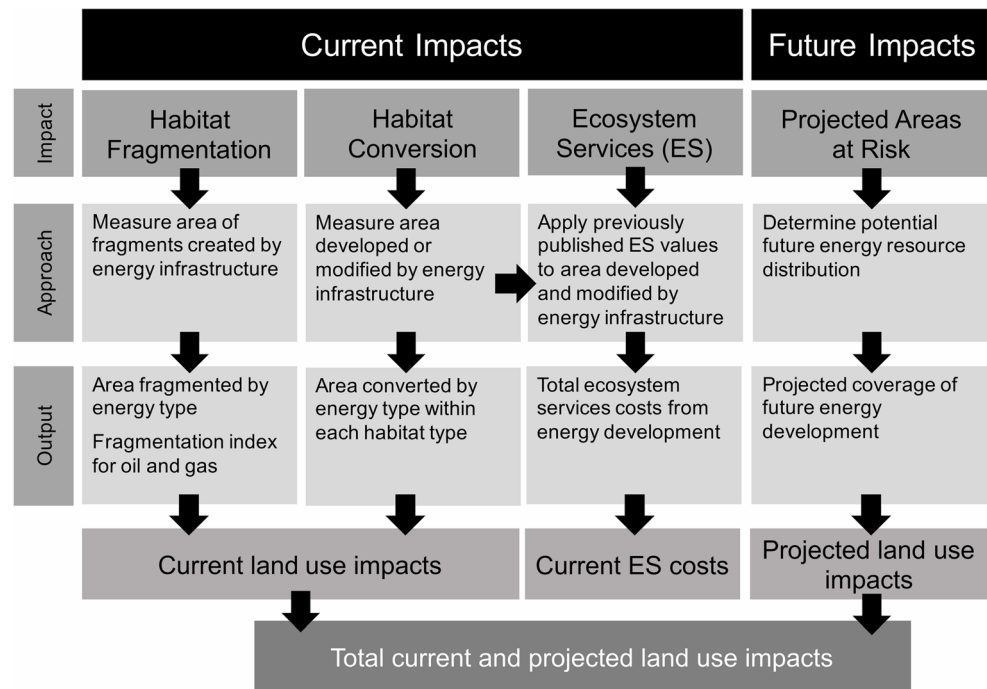
Results

In the US portion of the Chihuahuan Desert, conventional oil and gas development has grown rapidly since the early twentieth century (Fig. 2a) and is the largest source of anthropogenic change and ecosystem services costs (Table 1). In recent years, unconventional oil and gas has become the dominant source of new energy development, although its total impact is still relatively small (about 20%) compared to conventional oil

and gas. Amongst renewable energy sources, solar energy is growing rapidly, although still small in absolute value (less than 1% of oil and gas). Wind energy, while also small in absolute value, has not seen recent growth (Fig. 2b). The wind and solar industries have not modified or developed large amounts of land in the Chihuahuan Desert and are responsible for less than 1% of the total annual ecosystem services costs (Table 1). Of the three major habitat types found in the Chihuahuan Desert, desert shrubland habitat has been impacted the most. However, it appears that different energy industries are impacting different habitats. All current wind farms are located in desert grassland, while more than 95% of photovoltaic facilities are located in desert shrubland. The oil and gas industry has also, up to this point, primarily impacted desert shrubland habitat (Fig. S1 of Online Resource 1). Altogether, the annual ecosystem services costs due to energy-related land use changes in the Chihuahuan Desert are approximately \$182 million (2016 USD), the vast majority occurring in desert shrub habitat. The most prominent ecosystem services are climate regulation and raw materials. The Chihuahuan Desert stores moderate amounts of carbon and has marketable products (e.g., *Opuntia* cactus). Additionally, cultural benefits, including recreational and inspirational values that are lost with industrial development, compose a sizable proportion of the ES. These services together compose about 90% of the total estimated for the US Chihuahuan Desert (Taylor et al. 2017). These costs were concentrated in desert shrub habitat since this habitat is disproportionately affected because of the location of economically valuable oil and gas deposits. In addition, desert shrub habitat generally has higher annual carbon sequestration values compared to desert grasslands.

Fragmentation levels of the USGS quadrangles were highly correlated with well count ($p < 0.001$, $R^2 = 0.77$, equation: $\log_{10}y = -0.48(\log_{10}x) + 1.88$; Fig. S3a of Online Resource 1). The very high correlation coefficient indicates that well number per quadrangle is the largest predictor of fragmentation in the bioregion. According to the equation of the relationship between well count and median fragment size per quadrangle, the construction of five wells reduces median fragment size by 50%, while the construction of 112 wells reduces median fragment size by 90%. Well count was also significantly correlated with amount of edge habitat ($p < 0.001$, $R^2 = 0.54$, equation: $y = 411.80(\log_{10}x) + 232.57$; Fig. S3b of Online Resource 1). While we could not perform a regression analysis on the wind fragmentation, we did calculate the change in fragmentation in each wind farm location (Table S2 of Online Resource 1). Proportional changes in median fragment size ranged from 0.18 to 0.90, but it should be noted that there was high variation in turbine number and initial fragment size of each area measured. Weighted mean calculations estimated that each wind turbine created an average of 0.56 km of new edge habitat.

Fig. 1 Diagram illustrating our strategy for estimating current and future energy-related impacts on land use and ecosystem services of the US Chihuahuan Desert bioregion



Up through 2016, agriculture was the largest contributor to land development (i.e., total conversion of native vegetation), followed closely by energy, while urbanization was a smaller component (Table 2). Combined areas of development due to agriculture, urbanization, and energy industries were still small, occupying only about 5% of the land area. However, while agriculture and urban areas are typically locally concentrated in our study site, energy tended to sprawl over a much larger landscape, creating large amounts of fragmentation. When all sources of development and energy industry fragmentation are combined, about one-third of the US Chihuahuan Desert (about 10% of the entire US and Mexican Chihuahuan Desert bioregion) is highly impacted through direct development or fragmentation (Fig. 3). This amount represents about 58,000 km² of the total 214,000 km² of habitat located in the USA. Accordingly, about two-thirds of the US Chihuahuan Desert is currently undeveloped and relatively unfragmented (with the exception of some roads, including two major interstate highways and other infrastructure not accounted for in our fragmentation index model) in a corridor that extends from the Big Bend region into southeastern New Mexico and Arizona (Fig. 3, low and none quadrangles). Most recent oil and gas development has been occurring in existing intensive petroleum production areas, but current oil and gas leases indicate that some development is likely to spread outside of these areas (Fig. 4a). However, most leases fall within the traditional Permian Basin petroleum region in the eastern part of the bioregion. It should be noted that the density of leases is lower in New Mexico compared to Texas, probably due to higher public land ownership (and subsequently stronger

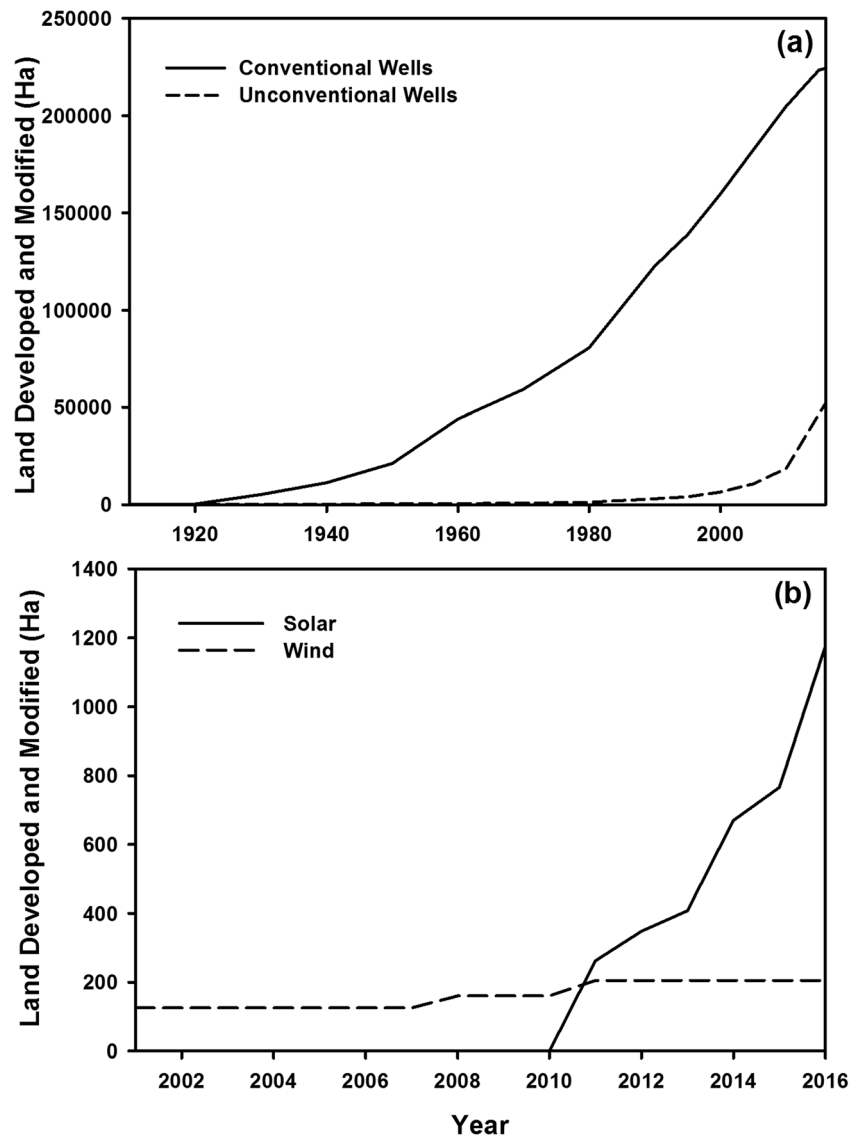
environmental regulations) in New Mexico. Although there is some overlap with the oil and gas leases, high solar and wind potential extends beyond this eastern area (Fig. 4b and c). Wind resources tend to be scattered throughout, while the best solar potential is concentrated in the western portion of our study area. Very little contiguous habitat would remain if all areas with high-energy potential were developed and the border wall fully constructed (Fig. 4d).

Discussion

Our results show that the past energy activity has developed and fragmented a considerable portion of the US Chihuahuan Desert, resulting in substantial ecosystem service costs. This process continues to expand in both well count and geographic coverage, especially as unconventional drilling has become the dominant source of new oil and gas activity. Wind and solar have also begun to expand into the bioregion and have potential to spread into areas that have, until now, experienced negligible development. The combination of past energy industry activity and the geographic pattern of future energy resources threatens to disrupt the remaining integrity of this biologically and culturally important landscape.

Although the US Chihuahuan Desert has been impacted greatly by past human development, particularly by energy industries, about two-thirds of it remains in a relatively undeveloped and unfragmented state, with the exception of a fairly low density of highways in the low fragmentation quadrangles. This condition and potential for long-term conservation is positive compared to many US bioregions that have been

Fig. 2 Land impacts over time of **a** conventional and unconventional oil and gas and **b** solar and wind industries on land use and modification within the US Chihuahuan Desert bioregion



severely impacted by agricultural and urban development (Hoekstra et al. 2005). Currently, a corridor stretching northwest from the Big Bend region of Texas into southern New Mexico and eastern Arizona remains mostly intact (Fig. 3). This corridor connects to a large portion of Chihuahuan Desert

located in northern Mexico, which includes several important large and unfragmented conservation areas (Cañón de Santa Helena and Maderas del Carmen Protected Areas). Species that require large, unfragmented habitat (e.g., *Puma concolor* and *Ursus americanus*) utilize this corridor and are rarely

Table 1 Area developed and modified, ecosystem services (ES) costs, and proportion of US Chihuahuan Desert habitat types affected by energy-related land use changes through 2016

Development type	Developed (Ha)	Modified (Ha)	Annual ES Cost (USD 2016)	Proportion Affected		
				Grassland	Shrubland	Woodland
Oil and gas						
Conventional	134,546	120,707	147,840,100	0.09	0.91	<0.01
Unconventional	36,159	24,931	33,977,203	0.12	0.88	0.00
Wind energy	213	177	132,842	1.00	0.00	0.00
Solar energy	1177	11	462,081	0.04	0.96	0.00
Total	172,095	145,826	182,412,226			

Table 2 Land development and fragmentation amount and proportion of total landscape for sources of development within the US Chihuahuan Desert bioregion

Source	Amount impacted (Ha)	Proportion of total
Agriculture (developed)	486,623	0.027
Urbanization (developed)	167,845	0.009
Energy (developed and modified)	317,921	0.018
Energy (fragmented)	4,900,305	0.270
Natural state (undeveloped/relatively unfragmented)	12,273,020	0.676
Total	18,145,714	

detected in the more developed parts of the Chihuahuan Desert (Onorato et al. 2004; Hellgren et al. 2005; Holbrook et al. 2012).

However, this corridor is at risk of future development and fragmentation, especially from the varied energy industries and political developments (i.e., the border wall). While up to now, energy development has been predominantly oil and gas, the greater risks to the undeveloped and unfragmented corridor

appear to the wind and solar. The greatest solar potential areas, if developed, would impact the western portion of the Chihuahuan Desert (Fig. 4c), although it is important to reiterate that practically all of the Chihuahuan Desert has solar resources adequate for commercial development (Pletka and Finn 2009). The best wind resources also extend over a large portion of the corridor, particularly in the southwest portion (Fig. 4b). The combination of wind and solar development, if developed to its full

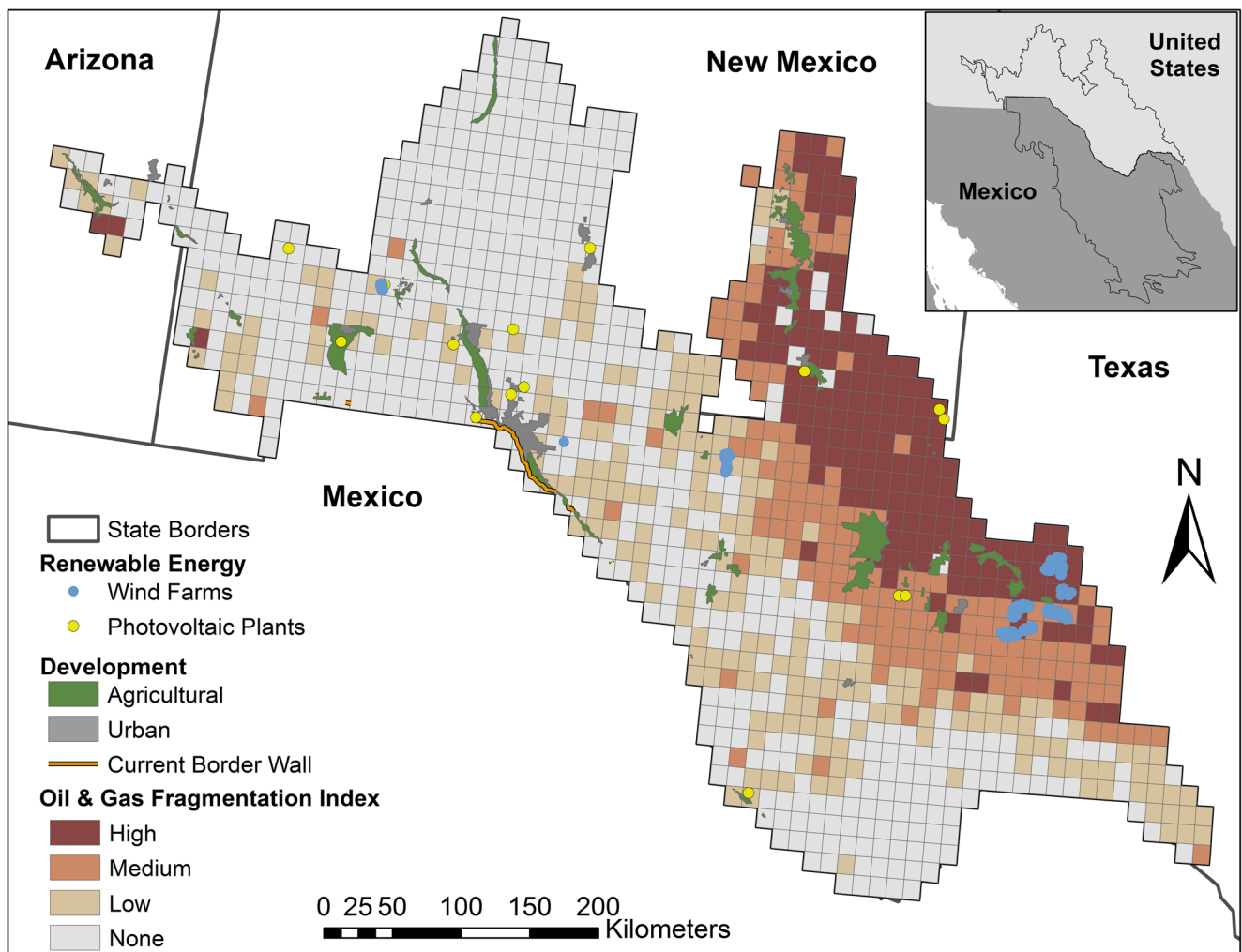


Fig. 3 Current impacts of various types of development, including fragmentation by oil and gas infrastructure, of the US Chihuahuan Desert bioregion. Oil and gas fragmentation index is defined as high (median fragment size reduced to >90% smaller than background),

medium (median fragment size reduced 50–90% smaller than background), low (median fragment size reduced 1–49% smaller than background), and none (no fragmentation from oil and gas development)

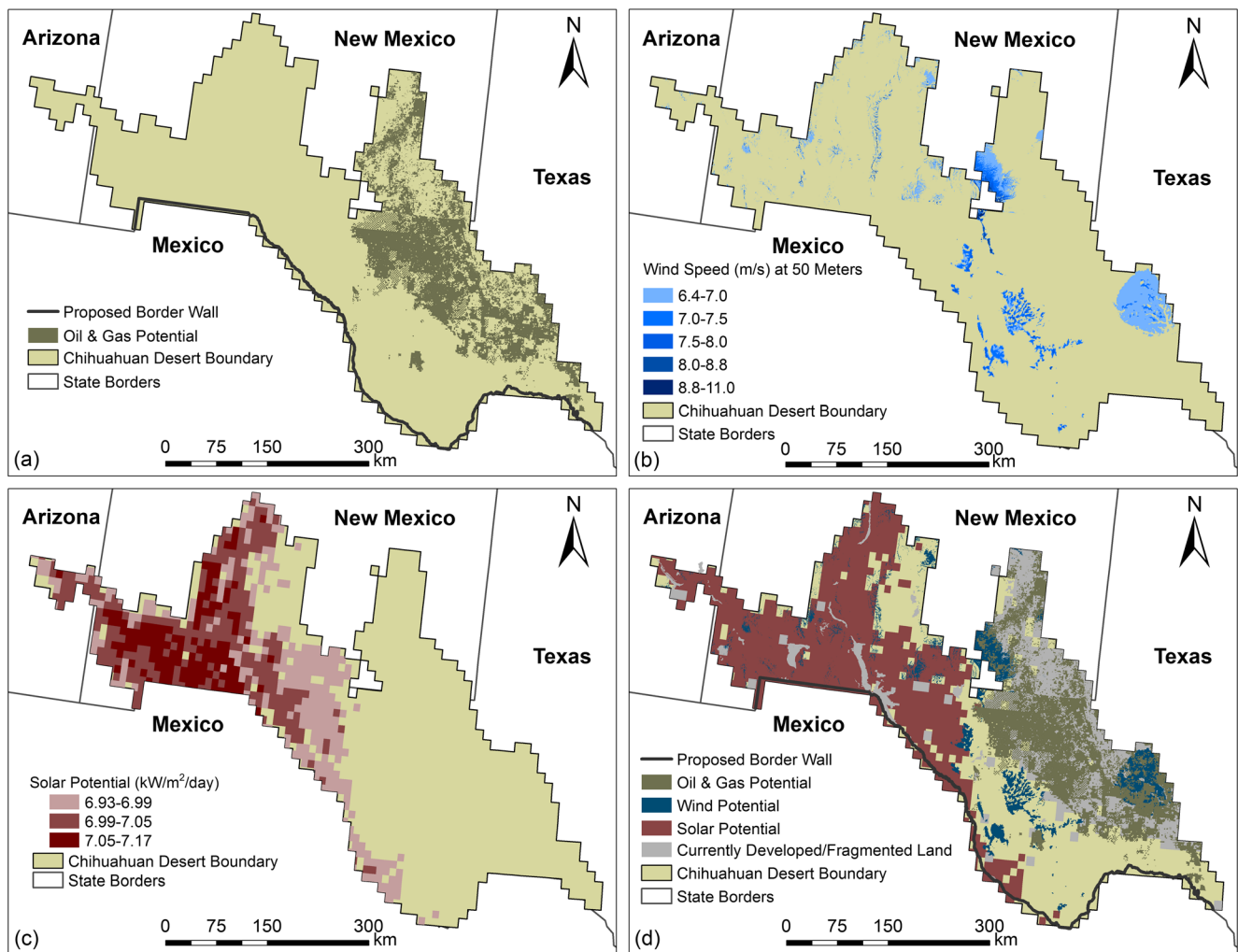


Fig. 4 Predictions for future development within the US Chihuahuan Desert based on resource availability. Maps show **a** oil and gas lease purchases from 2013 to 2017 plus proposed USA-Mexico border wall, **b** wind speed averages at 50 m that are considered economically feasible

for industrial wind development, **c** highest solar radiation levels, and **d** combined potential for development in the bioregion when all energy resources plus the USA-Mexico border wall are mapped together

potential, would drastically reduce the unfragmented area and connectivity between remaining habitats. Additionally, the proposed border wall, if completed as a pedestrian fence, would completely isolate the remaining US Chihuahuan Desert from the large areas of natural habitat in Mexico.

An important pattern demonstrated here is that the best renewable energy resources we identified tended to be in areas not already impacted by oil and gas development. This pattern is especially true for solar power, which would have its best locations outside of practically all of the intensive oil and gas drilling areas. Good wind power resources are, in part, located within the larger Permian Basin petroleum region. We contend that future wind developments should occur in high wind resource areas that overlap existing oil and gas drilling regions. This strategy would help avoid damage to the remaining higher quality habitat and have the added benefit of placing wind farms in places that have existing energy infrastructure. Most early wind and solar projects

have been established in or near existing developed and/or fragmented areas (Fig. 3), often near high voltage electrical transmission lines (EIA 2017). While this pattern is expected to continue, it is also likely that these developments could easily spread into areas with less existing infrastructure that have high ecological integrity. Regulations or incentives to site new wind, solar, and fossil fuel facilities near existing energy infrastructure would be a reasonable first step to mitigate against increased damage to this bioregion. These approaches to mitigation would be applicable to all three habitat types in this region and help conserve habitat connectivity.

If energy expansion occurs into the high resource areas and the proposed border wall proceeds, we suggest that some species would be lost from most or all of the US Chihuahuan Desert bioregion. For instance, the mountain lion (*P. concolor*) is unlikely to persist in the region without the currently intact corridor (Holbrook et al. 2012). Similarly, the

black bear (*U. americanus*) exists in the Chihuahuan Desert as a series of small populations in higher elevations of desert woodland areas connected by migration across less suitable lower elevation habitat (i.e., a metapopulation, Onorato et al. 2004; Hellgren et al. 2005). Fragmentation of habitat, even if only outside of the desert woodland areas, would probably make this species' survival untenable, in which case, we would lose a unique population of desert megafauna that survives in the modern world. Thus, the protection of low elevation habitats, which are probably more prone to development, will need to be a priority if we are to maintain these current populations. The proposed border wall is also a major risk to these populations which have important dispersal corridors into protected areas of Mexico (see Dinerstein et al. (2000) for important cross-border corridors). Conservation of important habitats within Mexico will also be necessary, although the relatively small human population and subsequent low amount of development in the Mexican Chihuahuan Desert region allows for the possibility of effective protection.

In addition to the ecological impacts, our results also show that past energy development is costing society considerable ecosystem services. While the ecosystem services costs of other important unconventional oil and gas regions have been estimated (Allred et al. 2015; Moran et al. 2017), this is the first estimate for the Permian Basin, the oil and gas field with the largest petroleum production in continental North America (EIA 2018). Our unconventional estimate alone (> 33 million USD per year; Table 1) adds about 13% to the national total of annual ecosystem services costs for this industry (Moran et al. 2017). While conventional oil and gas ecosystem services costs have not been estimated for other regions, the Chihuahuan Desert total is over one-half of the total annual unconventional costs for the entire USA.

There are over 22,000 wells (mostly conventional, DrillingInfo.com 2018) in this region that are plugged and abandoned, many of which have not been reclaimed and, therefore, continue to incur ecosystem services costs (through continued impacts of infrastructure on vegetation and other biological processes; McClung and Moran 2018). The rapid increase in unconventional well development occurring now will increase these costs further. We argue that restoration of plugged and abandoned wells could potentially regain the ecosystem service values (McClung and Moran 2018) and, if targeted in select areas, improve connectivity within the corridor. For example, about 300 wells occur in the Texas portion of our described corridor (Fig. S1), a relatively small subset of the total. Targeting these wells for reclamation, which exist in a broader area of relatively low well density (Fig. S1), would presumably reduce fragmentation and improve the probability of some species persisting. While our estimate of over \$180 million in annual ecosystem services costs is large, it is dwarfed by the overall economic activity generated by the greater Permian Basin oil and gas

industry (which is responsible for over 99% of ecosystem services costs; Table 1). Direct economic impact was estimated at \$95 billion, and direct employment was estimated at 244,000 in 2013 (Ewing et al. 2014). Production has since grown indicating that the direct economic activity is now larger. Therefore, we argue that fees imposed on the oil and gas industry and diverted toward land reclamation and restoration would not be prohibitive.

Long-term conservation of the US Chihuahuan Desert bioregion will require land conservation and maintenance of connectivity between distant areas (Bell et al. 2004), but these efforts will likely differ between states. In Texas, there are only small amounts of public land north of the Big Bend region. Public land ownership in Texas is small in acreage (Vincent et al. 2014), and support for increased public land ownership is low (Patoski 2000). However, more creative private tools such as conservation easements and community-based conservation programs (Curtin et al. 2002) have been successful in this area (Merenlender et al. 2004). The Marfa Grasslands and Davis Mountains areas, two particularly biodiverse locations (Desmond and Montoya 2006), now have extensive easements that allow landowners to retain their land in its relatively natural state but restrict future development (Bodin 2014; UNEP-WCMC 2018). These areas were targeted because of their unusual habitat characteristics and high species diversity. Other parts of the Chihuahuan Desert have seen the formation of groups (e.g., Malpai Borderlands Group) dedicated to conserving natural resources and the traditional ranching lifestyle. In New Mexico and Arizona where there are extensive areas of public lands in the Chihuahuan Desert bioregion, prevention of habitat fragmentation and alteration will have to be achieved through regulatory and/or legal avenues. This process will likely require changes in public opinion. The expansion of these types of programs (both public and private) could be effective and achieve the goals of long-term conservation. Lands connecting these current protected areas, even if they lack biological uniqueness, will need to be incorporated into any strategy that will maintain the US Chihuahuan Desert as a truly functional bioregion.

The future of energy development is highly unpredictable and dependent on a variety of economic factors, changing social preferences, and government policy. Our study has used the US Chihuahuan Desert bioregion to describe the current and future risks of energy development to land use and fragmentation for a region that still maintains relatively high habitat connectivity. The threats of the diversifying global energy economy have the potential to affect other bioregions in the world in similar ways, especially deserts which tend to have high wind and solar potential and, in some cases, large estimated unconventional oil and gas reserves. For instance, North Africa has geological formations with extremely high unconventional gas potential and also abundant renewable resources (Merzouk 2000; Himri et al. 2009). The large,

proximate populations of Europe have made the diverse energy development of this region economically feasible, and there is strong interest in this prospect (Club of Rome 2007; Czisch 2010; Lacher and Kumet 2011). Our study on the Chihuahuan Desert shows that it may be possible to develop energy resources in these environments in a way that could conserve existing landscape level ecological connectivity. However, if this conservation goal is to be achieved, long-term planning, wise placement of energy infrastructure, and concerted efforts to protect ecologically valuable lands will need to be implemented.

Conclusion

Energy development is currently costing over \$180 million USD annually in ecosystem services for the Chihuahuan Desert of the USA. These costs will only grow as this energy development continues to expand and diversify in the region. Until now, most energy-related development has been concentrated in about one-third of the bioregion, which has left about two-thirds of the Chihuahuan Desert relatively intact to support important ecological communities and several charismatic megafauna. Analysis of energy resources, in particular renewables like solar and wind, shows that future development would be economically feasible throughout much of the Chihuahuan Desert, including many of the relatively intact and biodiverse surviving areas. Conservation-oriented planning for energy development and targeted restoration of priority landscapes could reduce future net costs and enhance protection of surviving high quality regions of the US Chihuahuan Desert.

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