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Comparison of Recent Oil and Gas, Wind Energy, and Other Anthropogenic Landscape Alteration Factors in Texas Through 2014

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Abstract

Recent research assessed how hydrocarbon and wind energy expansion has altered the North American landscape. Less understood, however, is how this energy development compares to other anthropogenic land use changes. Texas leads U.S. hydrocarbon production and wind power generation and has a rapidly expanding population. Thus, for ~47% of Texas (~324,000 km^2), we mapped the 2014 footprint of energy activities (~665,000 oil and gas wells, ~5700 wind turbines, ~237,000 km oil and gas pipelines, and ~2000 km electrical transmission lines). We compared the footprint of energy development to non-energy-related activities (agriculture, roads, urbanization) and found direct landscape alteration from all factors affects ~23% of the study area (~76,000 km^2), led by agriculture (~16%; ~52,882 km^2). Oil and gas activities altered <1% of the study area (2081 km^2), with 838 km^2 from pipelines and 1242 km^2 from well pad construction—and that the median Eagle Ford well pad is 7.7 times larger than that in the Permian Basin (16,200 vs. 2100 m^2). Wind energy occupied <0.01% (~24 km^2), with ~14 km^2 from turbine pads and ~10 km^2 from power transmission lines. We found that edge effects of widely-distributed energy infrastructure caused more indirect landscape alteration than larger, more concentrated urbanization and agriculture. This study presents a novel technique to quantify and compare anthropogenic activities causing both direct and indirect landscape alteration. We illustrate this landscape-mapping framework in Texas for the Spot-tailed Earless Lizard (*Holbrookia lacerata*); however, the approach can be applied to a range of species in developing regions globally.

Keywords Energy sprawl · Hydraulic fracturing · Wind power generation · Urbanization · Ecological impacts

Introduction

This study mapped direct anthropogenic landscape alteration in 47% of Texas (~324,000 km^2; Fig. 1) and compared alteration resulting from agriculture, urbanization, low-intensity development, and roads with alteration from oil and gas well pads, hydrocarbon pipelines, wind generation turbines, and high-voltage transmission lines. While oil and gas infrastructure in North America was recently mapped (Allred et al. 2015), the relative contribution of pads or pipelines was not assessed. In addition, the National Land Cover Database (NLCD; Homer et al. 2015) includes land use classes for agriculture and urbanization; however, it is difficult to map alteration from roads and right-of-ways without the corresponding roadway line maps (TXDOT 2016). Furthermore, it is impossible to assess the relative extent of direct landscape alteration from energy development activities that may be mapped as “developed” and “barren land” classes using NLCD. Thus, this study fills an

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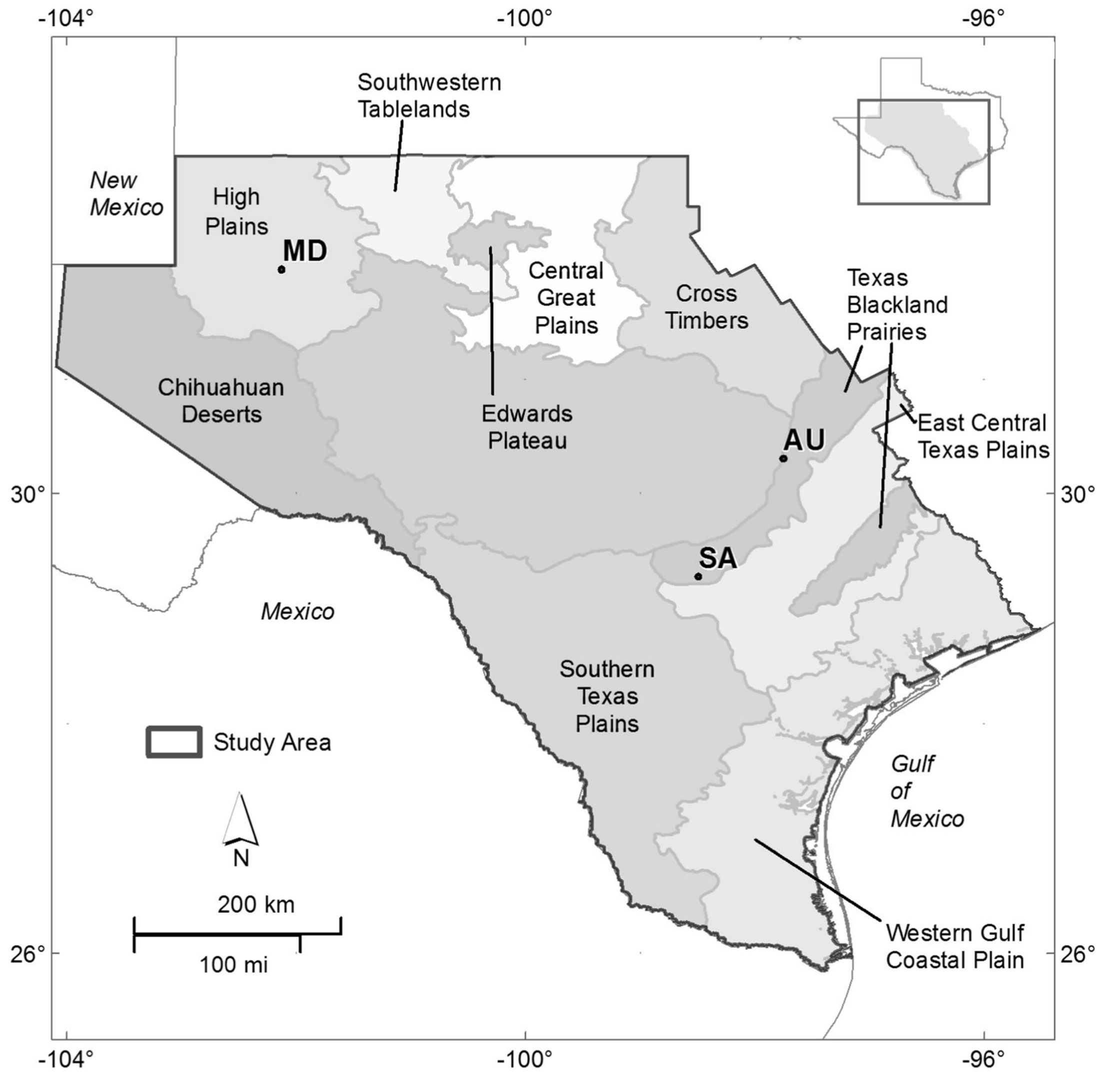

Fig. 1 Study area, including ecoregions (Omernik and Griffith 2014). The study area was selected to include the historic range of the Spot-tailed Earless Lizard (*Holbrookia lacerata*) in Texas. AU Austin, MD Midland, SA San Antonio

important need by mapping and comparing how much each non-energy and energy-related anthropogenic activity contributes to overall direct landscape alteration.

Understanding impacts from both direct and indirect anthropogenic landscape alteration is important because resulting changes in land cover threaten biodiversity globally (Fahrig 2003; McGarigal et al. 2005). Landscape alteration has also been identified as a main cause of wildlife extirpations and extinctions (Forman 2003; Juffe-Bignoli et al. 2014; Torres et al. 2016). Agriculture has been linked to habitat degradation and mortality (Gibbon et al. 2000; Sparling et al. 2010). Urbanization reduces habitat quantity and quality (Gibbon et al. 2000; McKinney 2008; Wolf et al. 2013). Road construction transforms and fragments habitat while directly causing mortality (Forman 2003; Andrews et al. 2008; Christie et al. 2015). Low-intensity development (such as rural development) and energy development has also been linked to habitat degradation (Finer et al. 2008; Brittingham et al. 2014; Christie et al. 2015), hydrologic alteration (King and Tennyson 1984; Trombulak and Frissell 2000; Pierre et al. 2015), habitat and vegetation fragmentation (Fahrig 2003; Hobbs et al. 2008; Drohan et al. 2012), and the spread of exotic species (Hansen and Clevenger 2005; Evangelista et al. 2011; Birdsall et al. 2012). In addition to effects to biodiversity, activities causing landscape alteration also may affect communities and water resources, but assessing these were outside of the scope of this study.

In North America, recent research has assessed anthropogenic landscape alteration from urbanization (Theobald 2003; Alig et al. 2004), road development (Pitman et al. 2005), and agricultural expansion (Huston 2005; Butsic and Brenner 2016). Other researchers have separately mapped landscape alteration resulting from energy development—

such as wind power (Diffendorfer and Compton 2014; Evans and Kiesecker 2014) and oil and gas extraction (Drohan et al. 2012; Pierre et al. 2015; Slonecker and Milheim 2015; Milt et al. 2016). Energy infrastructure development for hydrocarbons and wind has recently increased nationwide (Drohan and Brittingham 2012; Kiviat 2013; Diffendorfer and Compton 2014; Brand et al. 2014; Shrimali et al. 2015; Abrahams et al. 2015; Pierre et al. 2015). The combination of horizontal drilling and hydraulic fracturing revolutionized the oil and gas industry circa 2008 (Driskill et al. 2012; U.S. Government Accountability Offfice 2012). Since then, the footprint of oil and gas in North America has increased exponentially (Allred et al. 2015), causing estimated changes in land use as large as approximately three Yellowstone National Parks to accommodate this fossil fuel extraction infrastructure. Concurrently, wind energy expansion also rapidly converted land to meet human consumptive needs (Kuvlesky et al. 2007; McDonald et al. 2009; Diffendorfer and Compton 2014).

The effects of direct and indirect (e.g., edge effects) landscape alteration are species specific (Fischer and Lindenmayer 2007) and vary regionally (Jordaan et al. 2009). Some species may benefit from landscape modification while others may be adversely affected (Saunders et al. 1991). However, landscape alteration ultimately modifies the ecology of the surrounding landscape (Wilcove 1987; Saunders et al. 1991). Some species, such as those requiring interior habitat environments, lose habitats or their habitats are degraded. When landscape alteration occurs, landscape matrices change and may become more heterogeneous, food webs change, landscape patterns and patch sizes change, hydrology may change, and ultimately habitat impacts are farther reaching than just the direct landscape alteration (Fahrig 2002; Sawyer et al. 2006; Fischer and Lindenmayer 2007; Hebblewhite 2011; Pierre et al. 2015). Therefore, understanding both direct and indirect alteration created from each disturbance regime is essential to developing an integrated approach to landscape conservation and management (Saunders et al. 1991; Ryberg et al. 2017). For example, linear disturbances, such as access roads and pipelines, bisect contiguous habitat, facilitate the spread of invasive species (Barlow et al. 2017), and disrupt soil water and nutrient flow (Nasen et al. 2011).

Texas has been identified as a critical area in need of continued research assessing how surface infrastructure associated with urbanization, roads, agriculture, wind power, and oil and gas development has altered the landscape (Drohan et al. 2012; Jones and Pejchar 2013; Moran et al. 2015; Slonecker and Milheim 2015). Texas has five of the eleven fastest-growing cities in the United States (U.S. Census 2016). Forecasts of population growth from 2020–2070 estimate a 70% increase in future Texas residents. Texas also has several important oil and gas producing regions, including the Permian Basin and Eagle Ford Shale Play. In fact, Texas leads all U.S. states in hydrocarbon (EIA 2017) and wind energy production (Shrimali et al. 2015).

Less understood, however, is how recent individual anthropogenic factors contribute to landscape alteration—with associated edge effects—across the United States and in Texas—the geographic focus of this study. These trends suggest that expansion of the anthropogenic footprint due to urbanization, road construction, wind power generation, oil and gas extraction, and other resource development in Texas will increase in the future. Also important is evaluating the extent to which different anthropogenic factors increase landscape alteration through edge effects. For example, some activities perforate landscapes (e.g., well or turbine pads) while others (e.g., linear pipelines and roads) effectively bisect the landscape (Fahrig et al. 2011; Battisti et al. 2016; Pierre et al. 2017). Thus, a map of recent direct landscape alteration is urgently needed from which to compare future alteration. Therefore, this study created a high-resolution map of land use in 47% of Texas—including the footprint of energy infrastructure—which is not readily available from datasets such as the National Land Cover Dataset (Homer et al. 2015) or the Ecological Mapping System of Texas (Elliot et al. 2009).

The objective of this study was to quantify and compare direct landscape alteration and edge effects resulting from oil and gas infrastructure and wind energy development to other anthropogenic factors. Specifically, we:

(1) created a new dataset of the footprint of energy infrastructure as of 2014,
(2) mapped the surface footprint of all oil and gas occurring in our study area—which includes wells in the Eagle Ford Shale Play (unconventional) and Permian Basin (conventional and an increasing number of unconventional), and
(3) compared the relative impact of energy and non-energy-related development in the study area.

This study was motivated by conservation concerns regarding the Spot-tailed Earless Lizard (*Holbrookia lacerata*)—a lizard whose historic range included much of central and south Texas and has been petitioned for protection under the Endangered Species Act (Wild Earth Guardians 2010). Thus, the results of this study are being used to inform the U.S. Fish and Wildlife Service federal listing determination for the species—and can also be used to assess other environmental questions in the study area. We chose 2014 as the time period for our study due to availability of high-resolution aerial photography, which was the latest available to us at the start of this project. This detailed knowledge of regional land use trends should be of great interest to stakeholders needing to plan and mitigate future development, as well as establish a baseline for monitoring future changes on the landscape.

Materials and Methods

Study Area

We assessed direct landscape alteration for ~47% of Texas (~324,000 km^2) within the historic range of the Spot-tailed Earless Lizard in Texas (Fig. 1). The study area includes the metropolitan areas of Austin, San Antonio, and Midland and widely distributed agricultural activity. Also found in the study area are two major oil and gas regions—the Permian Basin and the expanding Eagle Ford Shale play (EIA 2017)—that recently experienced rapid growth as a result of increased use of hydraulic fracturing combined with directional drilling. Another expanding energy sector in the study area is wind energy development associated with the Competitive Renewable Energy Zone (Kuvlesky et al. 2007; Woodfin 2008).

Landscape Alteration

Data used to assess landscape alteration

We mapped direct landscape alteration resulting from a suite of anthropogenic factors using several datasets. The National Landcover Dataset (NLCD; Homer et al. 2015) was used to map alteration from agriculture and low-intensity development. The National Agricultural Imagery Program (NAIP) 1-m aerial photography (2014) was used to identify direct landscape alteration caused by oil and gas and wind power generation infrastructure. We downloaded all oil and gas wells (i.e., production, injection, horizontal, vertical, abandoned, wildcat, etc.) permitted within the study area as of October 24, 2014 from the IHS Enerdeq Database (IHS 2016). This date corresponded with the latest NAIP acquisition date in the study area. We acquired oil and gas pipeline networks from the Railroad Commission of Texas, the state oil and gas regulatory agency (RRC 2014). The locations of wind turbines installed as of December 31, 2014 were downloaded from the Federal Aviation Administration (FAA 2016). High voltage electrical transmission routes were plotted using approved 2011 Competitive Renewable Energy Zone lines. Roads and right-of-ways were assessed using the 2014 Texas Department of Transportation roadway inventory (TXDOT 2016) and 2015 TxDOT roadway lines (TXDOT 2016). Urban areas were plotted using the urbanized areas of Texas dataset (Texas Natural Resources Information System 2016). Non-energy-related landscape alteration was mapped directly using datasets, while energy-related development was mapped by creating derivative datasets—using the approaches described below. We assessed resulting alteration within Omernik Level III ecoregions (Omernik and Griffith 2014).

Mapping non-energy related development

All non-energy related development was mapped by using datasets directly, either by resampling raster datasets or by rasterizing polygon datasets. We first mapped urban areas using a dataset of urbanized areas in Texas (Texas Natural Resources Information System 2016). The polygon shapefile was converted to a 10-m resolution raster. To map roadway development, we followed the methods of Pierre et al. (2017), whose methodology utilizes the 2014 TxDOT roadway inventory (TXDOT Texas Department of Transportation 2015) buffered by the right-of-way (ROW) width and the 2015 TxDOT roadway lines areas (Texas Natural Resources Information System 2016). All buffered roadways and polyline roadways were converted to a 10-m resolution raster. We identified agricultural development by resampling the 30-m 2011 National Land Cover Dataset (NLCD; Homer et al. 2015) to 10-m resolution. We combined NLCD values for cropland and pasture (Table S1). Low-intensity development was mapped by combining the developed classifications from the resampled 10-m NLCD (Table S2).

Mapping energy related development

We created an entirely new land use/land change dataset, which mapped direct landscape alteration resulting from energy-related infrastructure development. The workflow we utilized to locate and map oil and gas drilling pad infrastructure is described in detail in Pierre et al. (2017); however, we provide a detailed summary of the approach here. We mapped direct landscape alteration using 1-m resolution National Agriculture Imagery Program (NAIP/USDA-NAIP 2014) aerial images acquired in 2014, which was the most recent available at start of the study. Iso cluster unsupervised image classification was executed in ArcGIS (version 10.2) to create 100 landscape classes (following the methods of Pierre et al. 2015 and Pierre et al. 2017), which were resampled to 10-m resolution and converted to polygons. Overlaps with roadways and urban areas were removed to create "bare-earth" polygons.

We mapped oil and gas drilling pad infrastructure by downloading all oil and gas wells permitted in the study area as of December 1, 2014 (i.e., production, injection, horizontal, vertical, abandoned, wildcat, etc.; IHS 2016). Wells permitted after October 24, 2014 were eliminated to correspond with the latest NAIP acquisition date in the study area. We did not consider wells coded as recompleted, re-drilled, or deepened, which we assumed to be a reworked existing well. Bare-earth polygons within 90 m of one or more wells were converted to a 10-m landscape-alteration raster. Wells without mapped alteration representing a well pad were either moved to an altered-landscape cluster or removed from the dataset. When wells occurred in alteration clusters larger than 4.5 ha (likely fallow agricultural fields or other bare ground not associated with a well pad), we assumed that alteration from pad development was immediately adjacent to the well and not throughout the whole cluster. Therefore, we only classified cells in these large alteration clusters within a 30-m radius of a well as caused by oil and gas operations. When two or more wells were located within 100 m of each other, we classified them as multiple wells on a single pad.

We mapped direct landscape alteration from oil and gas pipelines following the methods of Pierre et al. (2017) and applying a 30-m buffer to mapped pipelines. To map wind energy turbine pads, we selected turbines built as of December 31, 2014 and followed the methods of Pierre et al. (2017), which was similar to the approach to map oil and gas alteration, except wind turbine locations permitted by the FAA were used in lieu of permitted well locations. We mapped high voltage electricity transmission lines by manually editing 2011 approved routes based on visual inspection of NAIP imagery because as-built locations are not publicly available for security reasons. We applied a 30-m buffer to the edited high voltage transmission routes and followed the methods of Pierre et al. (2017) to extract alteration from the construction of this infrastructure.

We did not map access roads to either oil and gas (O&G) or wind pads as private access roads do not fall under the purview of TxDOT and these spatial data are not available. We recognize this as a limitation in our methodology and refer the reader to the "assumptions and limitations of landscape alteration assessment" section.

Hierarchical reclassification and summation of landscape alteration mapping

We used a hierarchical classification system to assign only one alteration type to pixels where several alteration factors overlapped following the schema in Table S2. We also classified any developed areas from the NLCD not overlapping with the urbanized layer as low-intensity development. We created maps of the individual anthropogenic factors and of the cumulative direct landscape alteration of all past and present human actions since a baseline, pre-Columbian landscape by summing landscape alteration from each individual factor. We summarized these results at 1-km^2 resolution and mapped them as percent alteration of a 1-km^2 cell to facilitate display. We also present direct landscape alteration results for each ecoregion.

Landscape alteration metrics

We evaluated the extent to which edge effects may increase the overall landscape footprint alteration for each anthropogenic activity. Consistent with landscape ecology practices, we mapped edge areas by applying a 100-m buffer to each alteration cluster (Howell et al. 2006; Jordaan et al. 2009; Johnson 2010; Svobodová et al. 2011; Drohan et al. 2012). We calculated the ratio of the area of edge to the area of the alteration cluster surrounded by the 100-m buffer. Thus, we used the edge–to–alteration ratio as an informative metric to inform how the shape of a landscape alteration cluster may increase the overall alteration area. For example, many small landscape alteration clusters, such as well pads, would have a higher edge–to–alteration ration than one, large altered area, such as an urban area.

Results

Cumulative Alteration

We found that 23.4% (75,786 km^2) of the landscape in the study area has been altered (Figs. 2, 3; Tables 1, 2). Much of this direct landscape alteration occurs to the east and south of a line between Austin and San Antonio. Additional areas of focused direct landscape alteration occur within a ~300 km radius north of Midland. When we examined direct landscape alteration by ecoregions (Table 2), we found that the Western Gulf Coastal Plain had the highest cumulative direct landscape alteration area (22,061 km^2), followed by the East Central Texas Plains (10,533 km^2). However, by percentage, the Texas Blackland Prairies had the largest percentage of alteration (9153 km^2, 63%). In contrast, the Chihuahuan Deserts had the lowest total alteration (1089 km^2, 3%).

Non-Energy-Related Development

We found that agriculture dominated non-energy-related anthropogenic direct landscape alteration that occurred since a pre-Columbian baseline (Figs. 3, 4a; Tables 1, 2). Conversion of pre-existing vegetation to agriculture altered 16.4% of the study area (52,882 km^2 and accounted for 70% of total alteration (Fig. 3). Agricultural alteration dominates in the southeastern and northern portions of the study area (Fig. 4a). We assessed two types of development. First, we found that low-intensity development altered 3.2% of the study area (13.6% of total direct landscape alteration; 10,304 km^2; Figs. 3, 4b) and was distributed throughout the entire study area. The most affected ecoregion from low-intensity development is the Texas Blackland Prairies and the least are the Edwards Plateau and the Chihuahuan

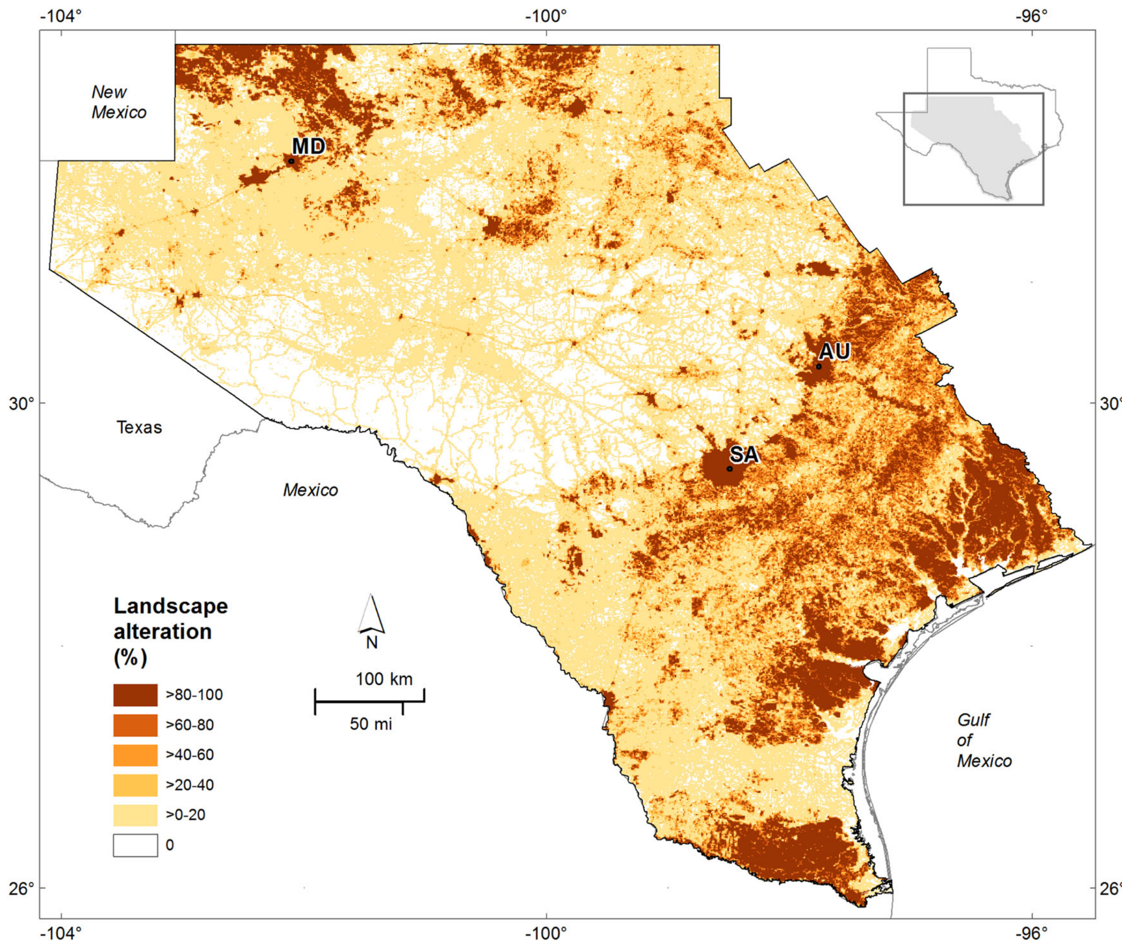

Fig. 2 Cumulative landscape alteration, showing the sum of energy and non-energy factors, expressed as percent alteration of a 1-km^2 cell. AU Austin, MD Midland, SA San Antonio

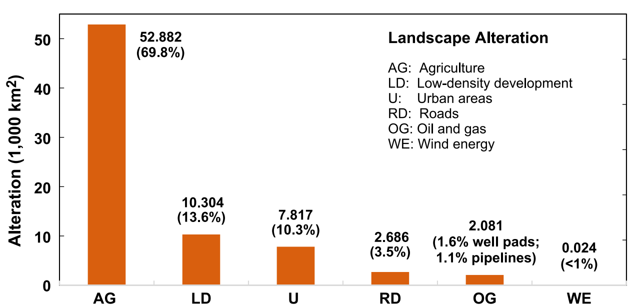

Fig. 3 Landscape alteration resulting from each anthropogenic factor. Landscape alteration values on figures are reported in square kilometers and, in parentheses, percentage of total landscape alteration resulting from each anthropogenic factor (due to rounding percentages do not add up to 100%)

Deserts (Tables 1, 2). Second, urbanization caused 10.3% of total direct landscape alteration (7817 km^2, 2.4% of study area; Figs. 3, 4c; Tables 1, 2) and—apart from Austin and San Antonio—is dispersed in towns throughout the study area. A comparison of 1-km^2 cells with at least one alteration pixel indicated that on average urbanization altered 64% of the cell and low-intensity development altered 5%. Roads altered 2686 km^2 of the landscape (0.8% of the study area; 4% of total alteration; Figs. 3, 4d; Tables 1, 2).

Energy-Related Development

Our mapped energy-related direct landscape alteration found that oil and gas extraction altered 2081 km^2 (0.6% of study area; 2.7% of the total alteration; Figs. 3, 4e). Of this, direct landscape alteration from well pads was 1243 km^2 and hydrocarbon pipelines was 839 km^2. All the ecoregions in the study area had oil and gas development, however, ≤1% of any given ecoregion was altered (Tables 1, 2). Other researchers have assessed the effects of oil and gas development to air, water quality, water demand, health, and social aspects (e.g., Nicot and Scanlon 2012; Vengosh et al. 2014); however, such assessments were outside the scope of this study. We also evaluated oil and gas pads in the study area ($n = 354{,}615$) and calculated pad sizes and numbers of wells per pad (Table 3) for the Eagle Ford Shale Play, which is dominated by unconventional wells (i.e., horizontal,

Table 1 Landscape alteration within each ecoregion resulting from each anthropogenic factor

Alteration by factor (km²)											
		Non-energy				Energy					
Ecoregion	UA	A	LD	U	RD	OG pads	OG pipelines	Wind pads	Wind transmission	Total alteration in ecoregion	Total ecoregion area
Western Gulf Coastal Plain	18,484.2	18,142.6	1584.9	1725.4	400.2	99.1	106.4	2.3	–	22,060.8	40,545.0
East Central Texas Plains	13,425.4	8711.3	1048.8	284.7	312.7	100.1	75.1	0.0	–	10,532.6	23,958.1
Southern Texas Plains	43,359.5	6723.1	2048.8	527.9	297.5	226.8	201.2	0.6	–	10,025.8	53,385.3
Texas Blackland Prairies	5471.1	5902.8	826.4	2092.6	278.0	34.5	18.2	–	–	9152.5	14,623.5
High Plains	17,589.9	6010.5	674.3	646.3	207.7	341.2	112.9	0.9	0.5	7994.3	25,584.2
Central Great Plains	16,292.4	3909.8	1069.0	568.9	236.0	46.2	21.0	0.8	1.9	5853.7	22,146.1
Edwards Plateau	70,936.4	424.1	1599.3	1250.2	451.1	165.9	126.8	6.0	4.1	4027.4	74,963.8
Cross Timbers	18,399.6	1588.1	899.5	513.1	235.8	33.6	26.7	0.5	2.4	3299.7	21,699.3
Southwestern Tablelands	8895.4	1222.9	309.4	84.5	86.6	31.3	13.0	2.2	0.7	1750.7	10,646.1
Chihuahuan Deserts	34,478.6	243.5	241.9	121.0	180.2	164.0	137.1	0.4	0.7	1088.9	35,567.5
Total	247,332.4	52,878.6	10,302.4	7814.6	2685.9	1242.7	838.4	13.5	10.4	75,786.4	
Edge–to–alteration ratio (km^2/km^2)	–	0.6	5.4	0.1	13.0	13.7	25.1	25.0	29.6	–	–

UA unaltered area, *A* agriculture, *LD* low-intensity development, *U* urbanized areas, *RD* roads, *OG pads* oil and gas drilling pads, *OG pipelines* oil and gas pipelines, *Wind pads* wind turbine pads, *Wind transmission* high voltage wind energy transmission lines

hydraulically fractured) and the Permian Basin, which is a mix of conventional wells (i.e., vertical), in addition to hydraulically fractured vertical wells and an increasing number of hydraulically-fractured horizontal wells.

Infrastructure development for wind power generation altered 24 km^2 (0.007%) of the study area and accounts for 0.03% of total alteration (Figs. 3, 4f). Of this, 14 km^2 was turbine pads (median pad side = 500 m^2) and 10 km^2 was from high voltage power transmission line infrastructure. The highest concentrations of alteration from wind were in the High Plains, Southwestern Tablelands, and the northern portion of the Edwards Plateau (Tables 1, 2). High concentrations of wind alteration also exist in the Western Gulf Plain region along the coast.

We also provide alteration data summarized at the county level in the Supplemental Results section to provide insight for practitioners involved with regional-scale planning and conservation efforts for the Spot-tailed Earless Lizard and other species of conservation concern. All data are available online for download at: https://doi.org/10.18738/T8/UDDPTE.

Landscape Alteration Metrics

We found that the edge–to–alteration ratio of non-energy factors (i.e., agriculture and urban areas) was lower than energy-related activities (i.e., wind power and oil and gas infrastructure; Table 1). For example, urbanization and agricultural development result in large, contiguous blocks of alteration with the lowest edge–to–alteration ratios, resulting in 0.1–0.6 km^2 of edge effect for every 1-km^2 of alteration (Table 1). Low-intensity development, which perforates landscapes, had a higher edge–to–alteration ratio (5.4). Roadway development, which bisects landscapes with relatively narrow corridors, had the highest non-energy edge–to–alteration ratio (13.0). We found alteration from energy-related activities generally affected smaller areas than non-energy factors; however, energy development had a consistently higher potential for creating edge effects. Linear alteration caused by construction of wind power transmission lines and oil and gas pipelines had the highest edge–to–alteration ratios (29.6 and 25.1, respectively). Pads for wind turbines had a higher edge–to–alteration ratio (25.0) than pads for oil and gas wells (13.7).

Discussion

Comparison of Landscape Alteration from Non-Energy and Energy-Related Development

We created novel direct landscape alteration datasets for energy-related infrastructure development—not specifically

Table 2 Percent of ecoregion altered by each anthropogenic factor

Percent of ecoregion altered by each factor									
	Non-energy					Energy			Total ecoregion alteration
Ecoregion	A	MD	U	TD	OG pads	OG pipelines	Wind pads	Wind transmission	
Texas Blackland Prairies	40.4	5.7	14.3	1.9	0.2	0.1	–	–	62.6
Western Gulf Coastal Plain	44.7	3.9	4.3	1.0	0.2	0.3	–	–	54.4
East Central Texas Plains	36.4	4.4	1.2	1.3	0.4	0.3	–	–	44.0
High Plains	23.5	2.6	2.5	0.8	1.3	0.4	–	–	31.1
Central Great Plains	17.7	4.8	2.6	1.1	0.2	0.1	–	–	26.5
Southern Texas Plains	12.6	3.8	1.0	0.6	0.4	0.4	–	–	18.8
Southwestern Tablelands	11.5	2.9	0.8	0.8	0.3	0.1	–	–	16.4
Cross Timbers	7.3	4.1	2.4	1.1	0.2	0.1	–	–	15.2
Edwards Plateau	0.6	2.1	1.7	0.6	0.2	0.2	–	–	5.4
Chihuahuan Deserts	0.7	0.7	0.3	0.5	0.5	0.4	–	–	3.1

UA unaltered area, *A* agriculture, *LD* low-intensity development, *U* urbanized areas, *RD* Roads, *OG pads* oil and gas drilling pads, *OG pipelines* oil and gas pipelines, *Wind pads* wind turbine pads, *Wind transmission* high voltage wind energy transmission lines

included in publicly available land cover datasets—and found that agriculture, including crops and pasture, was the most important direct landscape alteration factor in our ~324,000 km^2 study area (70% of total alteration; Figs. 3, 4). This was followed, in descending order, by low-intensity development (14% of total alteration), urbanization (10%), and roads (4%). We found that less than 4% of total direct landscape alteration was attributed to energy infrastructure, with 3% caused by oil and gas operations and less than 1% from wind power generation. An interesting finding of this work is how anthropogenic alteration plays out in the landscape. For instance, low-intensity development and roads are widely dispersed across the study area and alter a relatively low percent of any 1-km^2 cell we assessed (Figs. 4b, 4d). Agriculture, on the other hand, spans much of the Gulf Coast plains and High Plains and intensely alters the landscape where it occurs (Fig. 4a). Not surprisingly, urbanization from major cities (i.e., Austin and San Antonio) is focused along transportation corridors and alters a high percent of the landscape where it occurs (Fig. 4c). Conversely, we found that oil and gas development is widely dispersed across large areas of the state—particularly in the Permian Basin and Eagle Ford Shale Play—and that this development, where it occurs, alters a relatively low percent of the landscape (Fig. 4e). The pattern of direct landscape alteration caused by wind power generation is similar to that of oil and gas in that wind turbines—like wells—are constructed on rectilinear pads. Furthermore, the installation of power transmission lines—like pipelines—result in long, narrow swaths of direct landscape alteration. We also found that wind turbines and associated power transmission lines affected a much smaller area than oil and gas infrastructure.

Our analysis of edge–to–alteration ratios for each anthropogenic factor elucidated important overall effects that simply evaluating direct landscape alteration area did not reveal. For example, we found that alteration from energy-related activities had a higher edge–to–alteration ratio than non-energy activities. Our assessment also revealed that linear infrastructure installed for energy conveyance—whether electricity or hydrocarbons—had the highest potential for edge creation. Finally, while wind turbine pads had higher edge–to–alteration ratios than well pads, the greater number of oil and gas wells (~665,000) compared to wind turbines (~5700) highlights the overall importance of edge effects that resulted from drilling thousands of wells in the study area. One approach to mitigate the edge effects of well pad construction for oil and gas operators is to drill more multi-well pads.

Energy Sprawl: Growth of Oil and Gas Development and Wind Power Generation

This study mapped anthropogenic activities and their impact on the landscape as of 2014. However, this footprint is not static and we expect the relative contribution of each alteration factor to change in the future. This trend is of particular interest for the energy sector, and has been labeled "energy sprawl" (Trainor et al. 2016). For example, oil and gas energy resource development in Texas—such as the Eagle Ford, where the number of permitted wells has dropped from 5613 in 2014 to 1119 in 2016 (RRC 2017)—will continue expanding when oil prices rebound (West Texas Intermediate Crude was ~$53/barrel in March 2017, falling from > $100/barrel 2 years before; EIA 2017). For example, development in the Eagle Ford is expected to

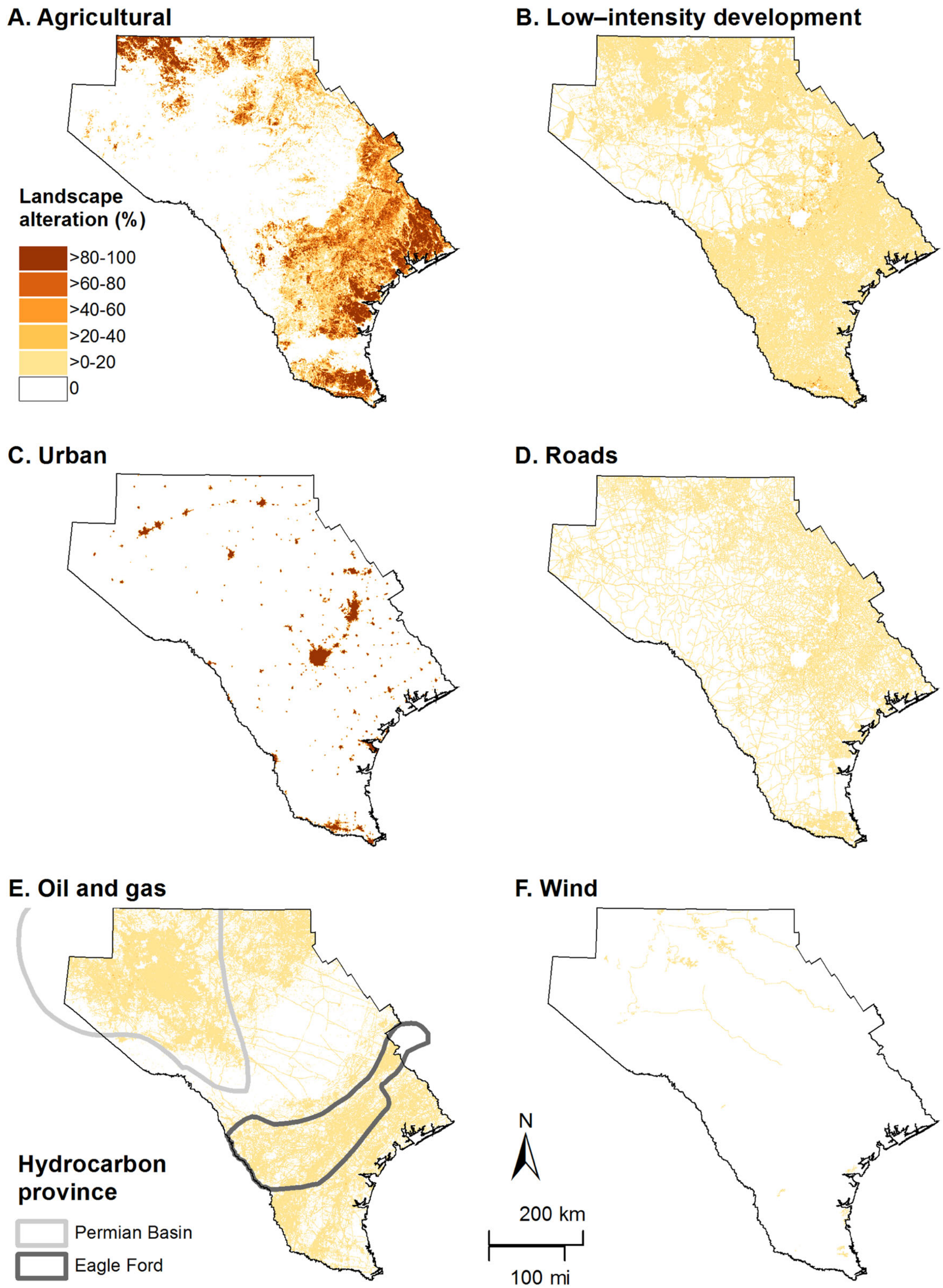

Fig. 4 Landscape alteration, expressed as percent alteration of a 1-km^2 cell, resulting from (**a**) agriculture, (**b**) low–intensity development, and (**c**) urbanized areas, (**d**) TxDOT roads, (**e**) oil and gas, and (**f**) wind energy

continue, with only 10% of wells drilled to date (Gong et al. 2013; Scanlon et al. 2014a, 2014b). In addition, wind power generation has also expanded recently, and Texas now produces more wind energy than any other state in the U.S. (Shrimali et al. 2015). We found that the overall physical footprint of energy development on the landscape in Texas

Table 3 Well pad size and number of wells per pad in Permian Basin and Eagle Ford Shale Play

Region	Number of Well pads	Well pad size (m^2)		Wells per pad	
		Mean	Median	Mean	Median
Study area	354,615	3619	1500	1.21	1
Permian Basin	195,713	3760	2100	1.15	1
Eagle Ford Shale Play	7076	16,970	16,200	2.02	2

is relatively small; however, we did not assess how this development may affect broader biophysical processes or ecological/biological systems.

Comparison of Well Pads in the Eagle Ford Shale Play and the Permian Basin

Our analysis of direct landscape alteration resulting from oil and gas infrastructure revealed that pads for wells in the Eagle Ford Shale Play were more than four times the size of pads in the Permian Basin. This result is consistent with the findings of other researchers who assessed oil and gas infrastructure and found pads for unconventional wells to be larger than their conventional counterpart (Johnson 2010). We also found that drilling pads across the study area have on average of 1.2 wells per pad. Thus, future drilling operations could mitigate their impact by increasing the number of wells per pad and by sharing existing oilfield roads and pipelines (Drohan et al. 2012). To this end, our research group is currently generating 50-year forecasts of possible future well pad locations and resulting landscape alteration for the Eagle Ford Shale Play and Permian Basin in Texas. These forthcoming results could be used by operators to optimize placement of oil and gas infrastructure that minimizes landscape alteration, and resulting potential impacts to species' habitat, erosion of soil, and degradation of watershed quality.

Implications for Conservation of Spot-tailed Earless Lizard and other Species with State and Federal Conservation Interests

Anthropogenic activities cause land use changes, which threaten biodiversity globally (Fahrig 2003); however, responses to landscape alteration are species-specific and span a broad range. This study is a first step in understanding what landscape alteration is occurring within habitats of species in our study area. Essential to biodiversity conservation—for the Spot-tailed Earless Lizard and other species—is identifying potential threats and developing mitigation strategies. The Texas Conservation Action Plan (TCAP; TPWD 2012) identifies species of conservation interest, threats to habitats, and proposes conservation strategies for dozens of terrestrial and aquatic species of state and federal interest. The TCAP specifically calls out population growth (i.e., urbanization), agricultural land management, and energy production and transmission (oil, gas, and wind) as priority issues potentially affecting species conservation at a state and ecoregion level. Thus, the landscape alteration analysis we completed for this study can be applied by other researchers working on conservation of dozens of species listed in the TCAP and found within our study area. One such species—which is the motivation for this study—is the Spot-tailed Earless Lizard. We suspect the Spot-tailed Earless Lizard to be an early successional species that may favor certain types of landscape alteration. However, invasive vegetation and fauna following changes in land-use may also adversely affect the species (Axtell 1998). As part of a larger research program for the Spot-tailed Earless Lizard, ongoing studies, including the use of radio telemetry, seek to improve our understanding of how the species responds to landscape alteration (Wolaver et al. 2018). Once these data become available, our mapping of landscape alteration could be used to inform conservation strategies. Additionally, the landscape alteration mapping of this study will be used directly by the U.S. Fish and Wildlife Service to help determine whether protection for the Spot-tailed Earless Lizard under the Endangered Species Act is warranted. Should pre-listing conservation efforts such as a Candidate Conservation Agreement with Assurances (CCAA) be implemented, the results of this study will also inform these management actions. Thus, while we focused on the historical range of the Spot-tailed earless lizard, our results can be used to improve conservation outcomes for other species of state and federal interest within this study area.

The goal of this study was to map and compare direct alteration from different landscape conversion regimes. However, it is important that land managers and planners also consider indirect impacts to the landscape as well. For instance, we have shown that patterns of direct landscape alteration from energy development results in a diffuse alteration of the landscape, whereas direct alteration from urban and agricultural expansion is larger and aggregated. We show these alteration types have different indirect edge impacts. In addition, the Texas Conservation Action Plans (Texas Parks and Wildlife Department 2012) highlight the potential threats of different alteration regimes within each ecoregion on habitats of species of interest and call for different mitigation strategies. For example, the widely-distributed linear features associated with access roads and transmission lines for wind and O&G development may create edge effects through interior habitats opening up predator corridors and pathways for invasive species. Additionally, Texas does not require operators to reclaim these areas with native seeds. In contrast, conversion to agricultural production not only creates habitat loss but also creates additional concerns with pesticide and fertilizer use, which may impact native fauna or adjacent water sources. Therefore, different mitigation strategies are suggested for each type of alteration. Examples may include incentivizing private landowners to reclaim lands altered by energy development with native plants and working with the energy industry to find creative ways to avoid, minimize, and mitigate impacts to listed and candidate species (Texas Parks and Wildlife Department 2012). These types of mitigation measures can be achieved by avoiding intact landscapes, minimizing the creation of new access roads, the use of multi-well pads, controlled site access, and reclamation with native plant species. Similarly, agricultural and urban expansion can be limited by the creation of conservation easements or creating incentives when possible to prevent further conversion of the landscape.

Future Research Directions

This study assessed the cumulative impact of all past and present anthropogenic landscape conversions and mapped how they altered the landscape in our study area. As part of a larger research program investigating the Spot-tailed Earless Lizard (Wolaver et al. 2018), the results of this study will feed into ongoing studies that seek to (1) improve our understanding of how landscape alteration affects the species and (2) understand potential future threats to the species. First, to understand the species' response to its environment, we are currently conducting radio telemetry studies at several sites within the historic range of the Spot-tailed Earless Lizard. The results of the telemetry studies will be used to test potential hypotheses of how land development, invasive species, fire suppression, and other factors may potentially affect the species throughout its potential modern range. Second, while we now understand present direct landscape alteration and will soon understand how this information can be used to develop on-the-ground conservation strategies, successful conservation of the species depends upon understanding its potential future threats. To this end, as part of the larger research program, we are currently forecasting the footprint of agriculture, urbanization, wind power development, oil and gas infrastructure, and other anthropogenic factors (Wolaver et al. 2018).

Assumptions and Limitations of Landscape Alteration Assessment

Our analysis used the best available data to map landscape alteration resulting from a suite of anthropogenic factors in 47% of Texas as of 2014. Despite several limitations in the approach we used, the results provide a useful tool to identify and compare the relative importance of contributors to landscape alteration at a regional scale. One potential limitation is a result of the large size of our study area. Other researchers conducting studies in smaller areas have manually digitized the footprint of oil and gas (Drohan et al. 2012). The geographic scope of our study necessitated using a semi-automated landscape classification approach following the methods of Pierre et al. (2017), which may not be as accurate as manually digitizing well pads and pipeline routes. Nevertheless, it was not practical for us to digitize the 354,615 oil and gas pads in the study area. Also, locations of wells drilled before the advent of surveys using GPS in the 1990s (IHS 2016) occasionally did not plot on a well pad apparent from visual inspection of aerial imagery. However, the approach of Pierre et al. (2017) corrected for these inaccuracies and associated each well with its correct well pad. In addition, we manually corrected the location of proposed high voltage electrical transmission routes so that our final routes matched aerial photo interpretation. We used a hierarchical approach in classifying direct landscape alteration that first assigned alteration to previously mapped urban and road areas when these alterations were co-located with newly mapped energy development, potentially underestimating some of the mapped energy infrastructure.

Because spatial databases of private access roads in oilfields and wind farms do not exist for private lands in Texas, we did not map these important causes of landscape alteration. While other studies that were constrained to a smaller study area have mapped (Johnson 2010) or estimated access roads (Jordaan et al. 2017), we chose to accept the limitation of not mapping access roads for multiple reasons. First, semi-automated-mapping approaches (e.g., Allred et al. 2015; Jordaan et al 2017; Pierre et al. 2017) do not effectively distinguish energy infrastructure access roads from contiguous mapped landscape alteration. Second, the manual digitization of landscape alteration from aerial imagery by a GIS analyst (e.g., Johnson 2010; Drohan et al. 2012; Pierre et al. 2015) is not a tractable approach to be used for studies such as this with a large regional spatial extent (~324,300 km^2). Thus, this study does not present landscape alteration caused by access roads to well pads or wind turbines. However, a study done in the Marcellus Shale (Drohan and Brittingham 2012) found the median of total disturbed area (pads, roads, compressor stations, etc,) to be 2.2 times larger than the median pad size. This suggests, at least for the Marcellus, the inclusion of roads (and other infrastructure) would double the direct landscape alteration caused by oil and gas well pad construction. Additionally, we would expect that indirect edge effects from oil and gas access roads to be similar to oil and gas pipelines and electrical transmission lines because they are also linear in nature. Thus, mapping privately-constructed access roads remains an important topic for future research. However, despite these limitations, our results provide an important, previously unavailable regional-scale mapping and comparison of energy infrastructure and non-energy related anthropogenic activities for almost half of Texas, which can be used as a foundational dataset to understand potential effects on species' habitats.

Conclusions

(1) Agricultural is the most important direct landscape alteration factor (70% of total alteration) and is spread throughout the study area, with the exception of the Edwards Plateau and Chihuahuan Desert ecoregions.

(2) Construction of energy infrastructure for oil and gas development (not including access roads) altered 1% of the study area and caused less than 4% of total alteration; however, forecasting future energy sprawl from potential infrastructure construction in the Eagle Ford Shale Play and Permian Basin is an important topic of ongoing research. We also found that well pads associated with drilling of unconventional wells (horizontal drilling using hydraulic fracturing) altered approximately four times the land area compared to drilling of conventional wells.

(3) Construction of wind turbines and power transmission lines contributed to less than 1% of total alteration; thus, despite recent wind generation expansion, the wind power footprint remains a minor, but growing landscape alteration factor.

(4) Energy development has a higher potential for edge effects than non-energy activities because pads for wells and turbines perforate and energy conveyance infrastructure bisects the landscape, compared to urbanization and agriculture, which have large, contiguous areas of alteration with relatively smaller edge areas.

This study presents a new approach to map and compare landscape alteration caused by energy- and non-energy related anthropogenic activities. We illustrate this landscape-assessment technique in Texas for the Spot-tailed Earless Lizard (*H. lacerata*). However, the approach should be of great interest to land planners, energy operators, wildlife biologists, and others evaluating and mitigating the relative impacts of a suite of anthropogenic factors for a range of species in developing regions globally.

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Compliance with Ethical Standards

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

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